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8

Testing of Synchronous Generators

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Testing of synchronous generators (SGs) is performed to obtain the steady-state performance characteristics and the circuit parameters for dynamic (transients) analysis. The testing methods may be divided into standard and research types. Tests of a more general nature are included in standards that are renewed from time to time to include recent well-documented progress in the art. Institute of Electrical and Electronics Engineers (IEEE) standards 115-1995 represent a comprehensive plethora of tests for synchronous machines.

New procedures start as research tests. Some of them end up later as standard tests. Standstill frequency response (SSFR) testing of synchronous generators for parameter estimation is such a happy case. In what follows, a review of standard testing methods and the incumbent theory to calculate the steady-state performance and, respectively, the parameter estimation for dynamics analysis is presented. In addition, a few new (research) testing methods with strong potential to become standards in the future are also treated in some detail.

Note that the term “research testing” may also be used with the meaning “tests to research for new performance features of synchronous generators.” Determination of flux density distribution in the airgap via search coil or Hall probes is such an example. We will not dwell on such “research testing methods” in this chapter.

The standard testing methods are divided into the following:

- Acceptance tests
- (Steady-state) performance tests
- Parameter estimation tests (for dynamic analysis)

From the nonstandard research tests, we will treat mainly “standstill step voltage response” and the on-load parameter estimation methods.

8.1 Acceptance Testing

According to IEEE standard 115-1995 SG, acceptance tests are classified as follows:

- A1: insulation resistance testing
- A2: dielectric and partial discharge tests
- A3: resistance measurements
- A4: tests for short-circuited field turns
- A5: polarity test for field insulation
- A6: shaft current and bearing insulation
- A7: phase sequence
- A8: telephone-influence factor (TIF)
- A9: balanced telephone-influence factor
- A10: line to neutral telephone-influence factor
- A11: stator terminal voltage waveform deviation and distortion factors
- A12: overspeed tests
- A13: line charging capacity
- A14: acoustic noise

8.1.1 A1: Insulation Resistance Testing

Testing for insulation resistance, including polarization index, influences of temperature, moisture, and voltage duration are all covered in IEEE standard 43-1974. If the moisture is too high in the windings, the insulation resistance is very low, and the machine has to be dried out before further testing is performed on it.

8.1.2 A2: Dielectric and Partial Discharge Tests

The magnitude, wave shape, and duration of the test voltage are given in American National Standards Institute (ANSI)–National Electrical Manufacturers Association (NEMA) MGI-1978. As the applied voltage is high, procedures to avoid injury to personnel are prescribed in IEEE standard 4-1978. The test voltage is applied to each electrical circuit with all the other circuits and metal parts grounded. During the testing of the field winding, the brushes are lifted. In brushless excitation SGs, the direct current (DC) excitation leads should be disconnected unless the exciter is to be tested simultaneously. The eventual diodes (thyristors) to be tested should be short-circuited but not grounded. The applied voltage may be as follows:

- Alternating voltage at rated frequency
- Direct voltage (1.7 times the rated SG voltage), with the winding thoroughly grounded to dissipate the charge
- Very low frequency voltage 0.1 Hz, 1.63 times the rated SG voltage

8.1.3 A3: Resistance Measurements

DC stator and field-winding resistance measurement procedures are given in IEEE standard 118-1978.

The measured resistance R_{test} at temperature t_{test} may be corrected to a specified temperature t_s :

$$R_s = R_{test} \frac{t_s + k}{t_{test} + k} \quad (8.1)$$

where $k = 234.5$ for pure copper (in °C).

The reference field-winding resistance may be DC measured either at standstill, with the rotor at ambient temperature, and the current applied through clamping rings, or from a running test at normal speed. The brush voltage drop has to be eliminated from voltage measurement.

If the same DC measurement is made at standstill, right after the SG running at rated field current, the result may be used to determine the field-winding temperature at rated conditions, provided the brush voltage drop is eliminated from the measurements.

8.1.4 A4–A5: Tests for Short-Circuited Field Turns and Polarity Test for Field Insulation

The purpose of these tests is to check for field-coil short-circuited turns, for number of turns/coil, or for short-circuit conductor size. Besides tests at standstill, a test at rated speed is required, as short-circuited turns may occur at various speeds. There are DC and alternating current (AC) voltage tests for the scope. The DC or AC voltage drop across each field coil is measured. A more than +2% difference between the coil voltage drop indicates possible short-circuits in the respective coils. The method is adequate for salient-pole rotors. For cylindrical rotors, the DC field-winding resistance is measured and compared with values from previous tests. A smaller resistance indicates that short-circuited turns may be present.

Also, a short-circuited coil with a U-shaped core may be placed to bridge one coil slot. The U-shaped core coil is placed successively on all rotor slots. The field-winding voltage or the impedance of the winding voltage or the impedance of the exciting coil decreases in case there are some short-circuited turns in the respective field coil. Alternatively, a Hall flux probe may be moved in the airgap from pole to pole and measures the flux density value and polarity at standstill, with the field coil DC fed at 5 to 10% of rated current value.

If the flux density amplitude is higher or smaller than that for the neighboring poles, some field coil turns are short-circuited (or the airgap is larger) for the corresponding rotor pole. If the flux density does not switch polarity regularly (after each pole), the field coil connections are not correct.

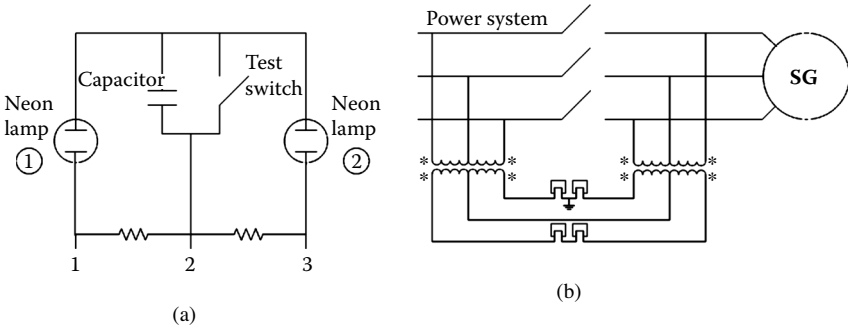


FIGURE 8.1 Phase-sequence indicators: (a) independent (1–2–3 or 1–3–2) and (b) relative to power grid.

8.1.5 A6: Shaft Current and Bearing Insulation

Irregularities in the SG magnetic circuit lead to a small axial flux that links the shaft. A parasitic current occurs in the shaft, bearings, and machine frame, unless the bearings are insulated from stator core or from rotor shaft. The presence of pulse-width modulator (PWM) static converters in the stator (or rotor) of SG augments this phenomenon. The pertinent testing is performed with the machine at no load and rated voltage. The voltage between shaft ends is measured with a high impedance voltmeter. The same current flows through the bearing radially to the stator frame.

The presence of voltage across bearing oil film (in uninsulated bearings) is also an indication of the shaft voltage.

If insulated bearings are used, their effectiveness is checked by shorting the insulation and observing an increased shaft voltage. Shaft voltage above a few volts, with insulated bearings, is considered unacceptable due to bearing in-time damage. Generally, grounded brushes in shaft ends are necessary to prevent it.

8.1.6 A7: Phase Sequence

Phase sequencing is required for securing given rotation direction or for correct phasing of a generator prepared for power bus connection. As known, phase sequencing can be reversed by interchanging any two armature (stator) terminals.

There are a few procedures used to check phase sequence:

- With a phase-sequence indicator (or induction machine)
- With a neon-lamp phase-sequence indicator (Figure 8.1a and Figure 8.1b)
- With the lamp method (Figure 8.1b)

When the SG no-load voltage sequence is 1–2–3 (clockwise), the neon lamp 1 will glow, while for the 1–3–2 sequence, the neon lamp 2 will glow. The test switch is open during these checks. The apparatus works correctly if, when the test switch is closed, both lamps glow with the same intensity (Figure 8.1a).

With four voltage transformers and four lamps (Figure 8.1b), the relative sequence of SG phases to power grid is checked. For direct voltage sequence, all four lamps brighten and dim simultaneously. For the opposite sequence, the two groups of lamps brighten and dim one after the other.

8.1.7 A8: Telephone-Influence Factor (TIF)

TIF is measured for the SG alone, with the excitation supply replaced by a ripple-free supply. The step-up transformers connected to SG terminals are disconnected. TIF is the ratio between the weighted root mean squared (RMS) value of the SG no-load voltage fundamental plus harmonic E_{TIF} and the rms of the fundamental E_{rms} :

$$TIF = \frac{E_{TIF}}{E_{rms}} ; \quad E_{TIF} = \sqrt{\sum_{n=1}^{\infty} (T_n E_n)} \quad (8.2)$$

T_n is the TIF weighting factor for the n th harmonic. If potential (voltage) transformers are used to reduce the terminal voltage for measurements, care must be exercised to eliminate influences on the harmonics content of the SG no-load voltage.

8.1.8 A9: Balanced Telephone-Influence Factor

For a definition, see IEEE standard 100-1992.

In essence, for a three-phase wye-connected stator, the TIF for two line voltages is measured at rated speed and voltage on no-load conditions. The same factor may be computed (for wye connection) for the line to neutral voltages, excluding the harmonics 3,6,9,12,

8.1.9 A10: Line-to-Neutral Telephone-Influence Factor

For machines connected in delta, a corner of delta may be open, at no load, rated speed, and rated voltage. The TIF is calculated across the open delta corner:

$$Residual \ TIF = \frac{E_{TIF(open\delta)}}{3E_{rms(one\ phase)}} \quad (8.3)$$

Protection from accidental measured overvoltage is necessary, and usage of protection gap and fuses to ground the instruments is recommended.

For machines that cannot be connected in delta, three identical potential transformers connected in wye in the primary are open-delta connected in their secondaries. The neutral of the potential transformer is connected to the SG neutral point.

All measurements are now made as above, but in the open-delta secondary of the potential transformers.

8.1.10 A11: Stator Terminal Voltage Waveform Deviation and Distortion Factors

The line to neutral TIF is measured in the secondary of a potential transformer with its primary that is connected between a SG phase terminal and its neutral points. A check of values balanced, residual, and line to neutral TIFs is obtained from the following:

$$line \ to \ neutral \ TIF = \sqrt{(balanced \ TIF)^2 + (residual \ TIF)^2} \quad (8.4)$$

Definitions of deviation factor and distortion factor are given in IEEE standard 100-1992. In principle, the no-load SG terminal voltage is acquired (recorded) with a digital scope (or digital data acquisition system) at high speed, and only a half-period is retained (Figure 8.2).

The half-period time is divided into J (at least 18) equal parts. The interval j is characterized by E_j . Consequently, the zero-to-peak amplitude of the equivalent sine wave E_{OM} is as follows:

$$E_{OM} = \sqrt{\frac{2}{J} \sum_{j=1}^J E_j^2} \quad (8.5)$$

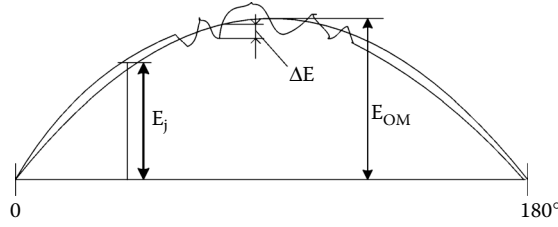


FIGURE 8.2 No-load voltage waveform for deviation factor.

A complete cycle is needed when even harmonics are present (fractionary windings). Waveform analysis may be carried out by software codes to implement the above method. The maximum deviation is ΔE (Figure 8.2). Then, the deviation factor $F_{\Delta EV}$ is as follows:

$$F_{\Delta EV} = \frac{\Delta E}{E_{OM}} \quad (8.6)$$

Any DC component E_o in the terminal voltage waveform has to be eliminated before completing waveform analysis:

$$E_o = \frac{\sum_{i=1}^N E_i}{N} \quad (8.7)$$

with N equal to the samples per period.

When subtracting the DC component E_o from the waveform E_i , E_j is obtained:

$$E_j = E_i - E_o \quad ; \quad j=1, \dots, N \quad (8.8)$$

The rms value E_{rms} is, thus,

$$E_{rms} = \sqrt{\frac{1}{N} \sum_{j=1}^n E_j^2} \quad ; \quad E_{OM} = \sqrt{2} E_{rms} \quad (8.9)$$

The maximum deviation is searched for after the zero crossing points of the actual waveform and of its fundamental are overlapped. A Fourier analysis of the voltage waveform is performed:

$$a_n = \frac{2}{N} \sum_{j=1}^n E_j \cos \frac{2\pi nj}{N}$$

$$b_n = \frac{2}{N} \sum_{j=1}^n E_j \sin \frac{2\pi nj}{N} \quad (8.10)$$

$$E_n = \sqrt{a_n^2 + b_n^2}$$

$$\phi_n = \tan^{-1}(b_n / a_n) \quad \text{for } a_n > 0$$

$$\phi_n = \tan^{-1}(b_n / a_n) + \pi \quad \text{for } a_n < 0$$

The distortion factor $F_{\Delta i}$ represents the ratio between the RMS harmonic content and the rms fundamental:

$$F_{\Delta i} = \frac{\sqrt{\sum_{n=2}^{\infty} E_n^2}}{E_{rms}} \quad (8.11)$$

There are harmonic analyzers that directly output the distortion factor $F_{\Delta i}$. It should be mentioned that $F_{\Delta i}$ is limited by standards to rather small values, as detailed in [Chapter 7](#) on SG design.

8.1.12 A12: Overspeed Tests

Overspeed tests are not mandatory but are performed upon request, especially for hydro or thermal turbine-driven generators that experience transient overspeed upon loss of load. The SG has to be carefully checked for mechanical integrity before overspeeding it by a motor (it could be the turbine [prime mover]).

If overspeeding above 115% is required, it is necessary to pause briefly at various speed steps to make sure the machine is still OK. If the machine has to be excited, the level of excitation has to be reduced to limit the terminal voltage at about 105%. Detailed inspection checks of the machine are recommended after overspeeding and before starting it again.

8.1.13 A13: Line Charging Capacity

Line charging represents the SG reactive power capacity when at synchronism, at zero power factor, rated voltage, and zero field current. In other words, the SG behaves as a reluctance generator at no load.

Approximately,

$$Q_{charge} \approx \frac{3V_{ph}^2}{X_d} \quad (8.12)$$

where

X_d = the d axis synchronous reactance

V_{ph} = the phase voltage (RMS)

The SG is driven at rated speed, while connected either to a no-load running overexcited synchronous machine or to an infinite power source.

8.1.14 A14: Acoustic Noise

Airborne sound tests are given in IEEE standard 85-1973 and in ANSI standard C50.12-1982. Noise is undesired sound. The duration in hours of human exposure per day to various noise levels is regulated by health administration agencies.

An omnidirectional microphone with amplifier weighting filters, processing electronics, and an indicating dial makes a sound-level measuring device. The ANSI “A” “B” “C” frequency domain is required for noise control and its suppression according to pertinent standards.

8.2 Testing for Performance (Saturation Curves, Segregated Losses, Efficiency)

In large SGs, the efficiency is generally calculated based on segregated losses, measured in special tests that avoid direct loading.

Individual losses are as follows:

- Windage and friction loss
- Core losses (on open circuit)
- Stray-load losses (on short-circuit)
- Stator (armature) winding loss: $3I_s^2R_a$ with R_a calculated at a specified temperature
- Field-winding loss $I_{fd}^2R_{fd}$ with R_{fd} calculated at a specified temperature

Among the widely accepted loss measurement methods, four are mentioned here:

- Separate drive method
- Electric input method
- Deceleration (retardation) method
- Heat transfer method

For the first three methods listed above, two tests are run: one with open circuit and the other with short-circuit at SG terminals. In open-circuit tests, the windage-friction plus core losses plus field-winding losses occur. In short-circuit tests, the stator-winding losses, windage-friction losses, and stray-load losses, besides field-winding losses, are present.

During all these tests, the bearings temperature should be held constant. The coolant temperature, humidity, and gas density should be known, and their appropriate influences on losses should be considered. If a brushless exciter is used, its input power has to be known and subtracted from SG losses. When the SG is driven by a prime mover that may not be uncoupled from the SG, the prime-mover input and losses have to be known. In vertical shaft SGs with hydraulic turbine runners, only the thrust-bearing loss corresponding to SG weight should be attributed to the SG.

Dewatering with runner seal cooling water shutoff of the hydraulic turbine generator is required. Francis and propeller turbines may be dewatered at standstill and, generally, with the manufacturer's approval. To segregate open-circuit and short-circuit loss components, the no-load and short-circuit saturation curves must also be obtained from measurements.

8.2.1 Separate Driving for Saturation Curves and Losses

If the speed can be controlled accurately, the SG prime mover can be used to drive the SG for open-circuit and short-circuit tests, but only to determine the saturation open-circuit and short-circuit curves, not to determine the loss measurements.

In general, a "separate" direct or through-belt gear coupled to the SG motor has to be used. If the exciter is designed to act in this capacity, the best case is met. In general, the driving motor 3 to 5% rating corresponds to the open-circuit test. For small- and medium-power SGs, a dynamometer driver is adequate, as the torque and speed of the latter are measured, and thus, the input power to the tested SG is known.

But today, when the torque and speed are estimated, in commercial direct-torque-controlled (DTC) induction motor (IM) drives with PWM converters, the input to the SG for testing is also known, thereby eliminating the dynamometer and providing for precise speed control ([Figure 8.3](#)).

8.2.1.1 The Open-Circuit Saturation Curve

The open-circuit saturation curve is obtained when driving the SG at rated speed, on open circuit, and acquiring the SG terminal voltage, frequency, and field current.

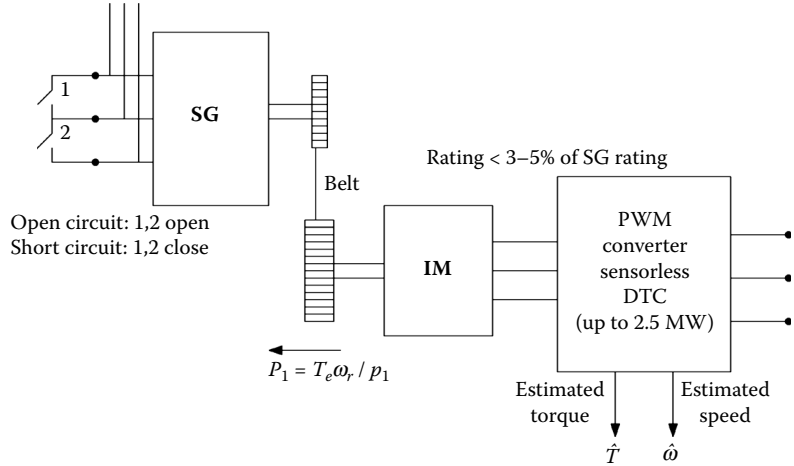


FIGURE 8.3 Driving the synchronous generator for open-circuit and short-circuit tests.

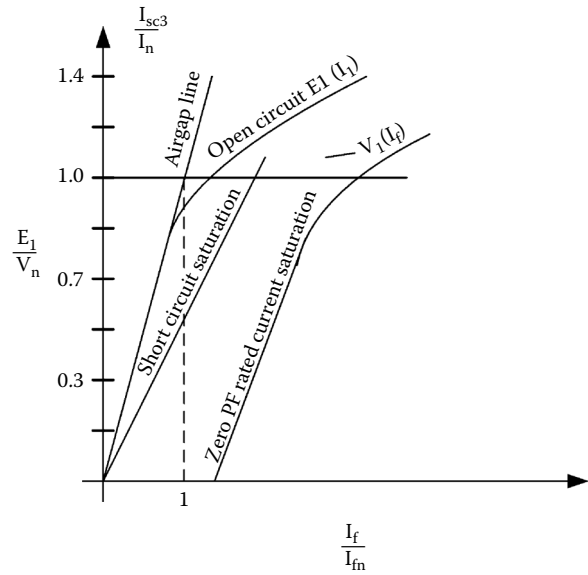


FIGURE 8.4 Saturation curves.

At least six readings below 60%, ten readings from 60 to 110%, two from 110 to 120%, and one at about 120% of rated speed voltage are required. A monotonous increase in field current should be observed. The step-up power transformer at SG terminals should be disconnected to avoid unintended high-voltage operation (and excessive core losses) in the latter.

When the tests are performed at lower than rated speed (such as in hydraulic units), corrections for frequency (speed) have to be made. A typical open-circuit saturation curve is shown in Figure 8.4. The airgap line corresponds to the maximum slope from origin that is tangent to the saturation curve.

8.2.1.2 The Core Friction Windage Losses

The aggregated core, friction, and windage losses may be measured as the input power P_{10} (Figure 8.3) for each open-circuit voltage level reading. As the speed is kept constant, the windage and friction losses

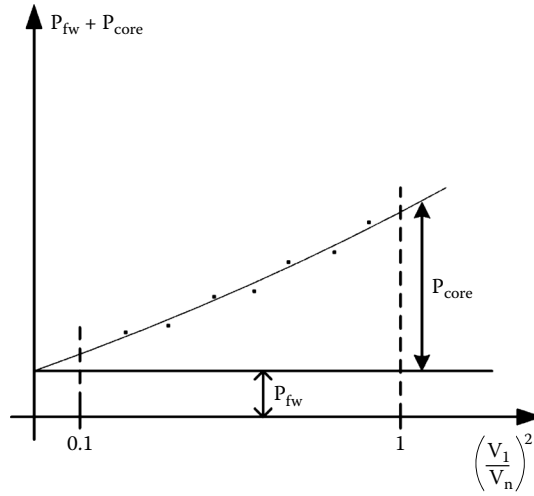


FIGURE 8.5 Core (P_{core}) and friction windage (P_{fw}) losses vs. armature voltage squared at constant speed.

are constant ($P_{fw} = \text{constant}$). Only the core losses P_{core} increase approximately with voltage squared (Figure 8.5).

8.2.1.3 The Short-Circuit Saturation Curve

The SG is driven at rated speed with short-circuited armature, while acquiring the stator and field currents I_{sc} and I_f . Values should be read at rated 25%, 50%, 75%, and 100%. Data at 125% rated current should be given by the manufacturer, to avoid overheating the stator. The high current points should be taken first so that the temperature during testing stays almost constant. The short-circuit saturation curve (Figure 8.4) is a rather straight line, as expected, because the machine is unsaturated during steady-state short-circuit.

8.2.1.4 The Short-Circuit and Strayload Losses

At each value of short-circuit stator current, I_{sc} , the input power to the tested SG (or the output power of the drive motor) P_{isc} is measured. Their power contains the friction, windage losses, the stator winding DC losses ($3I_{sc}^2 R_{adc}$), and the strayload loss P_{stray} load (Figure 8.6):

$$P_{isc} = P_{fw} + 3I_{sc}^2 R_{adc} + P_{strayload} \quad (8.13)$$

During the tests, it may happen that the friction windage loss is modified because temperature rises. For a specified time interval, an open-circuit test with zero field current is performed, when the whole loss is the friction windage loss ($P_{10} = P_{fw}$). If P_{fw} varies by more than 10%, corrections have to be made for successive tests.

Advantage may be taken of the presence of the driving motor (rated at less than 5% SG ratings) to run zero-power load tests at rated current and measure the field current I_f , terminal voltage V_1 ; from rated voltage downward.

A variable reactance is required to load the SG at zero power factor. A running, underexcited synchronous machine (SM) may constitute such a reactance, made variable through its field current. Adjusting the field current of the SG and SM leads to voltage increasing points on the zero power factor saturation curve (Figure 8.4).

8.2.2 Electric Input (Idle-Motoring) Method for Saturation Curves and Losses

According to this method, the SG performs as an unloaded synchronous motor supplied from a variable voltage constant frequency power rating supply. Though standards indicate to conduct these tests at rated

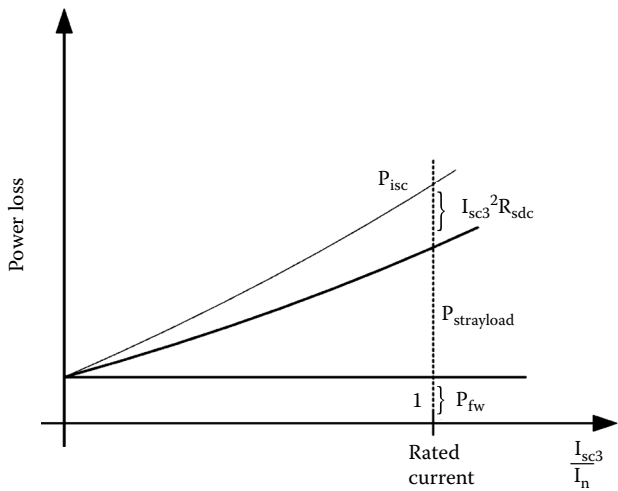


FIGURE 8.6 Short-circuit test losses breakdown.

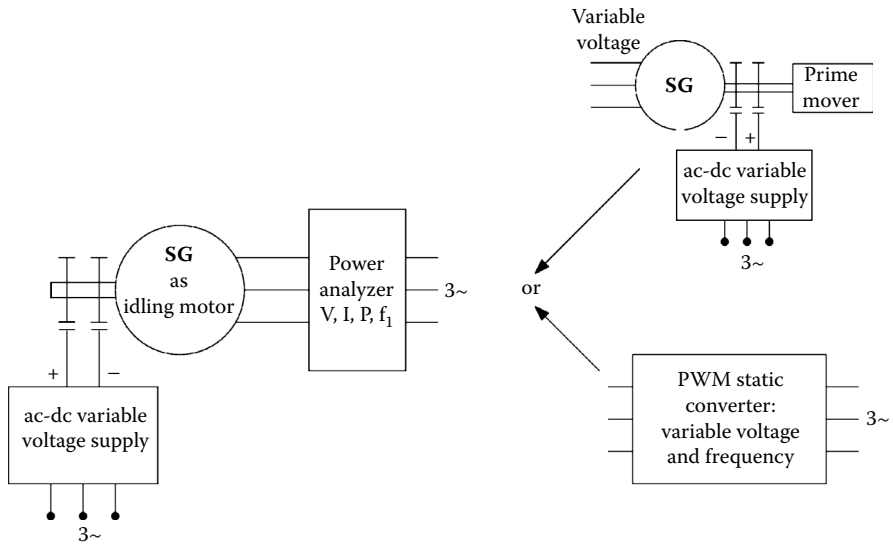


FIGURE 8.7 Idle motoring test for loss segregation and open-circuit saturation curve.

speed only, there are generators that also work as motors. Gas-turbine generators with bidirectional static converters that use variable speed for generation and turbine starting as a motor are a typical example. The availability of PWM static converters with close to sinusoidal current waveforms recommends them for the no-load motoring of SG. Alternatively, a nearly lower rating SG (below 3% of SG rating) may provide for the variable voltage supply.

The testing scheme for the electric input method is described in Figure 8.7.

When supplied from the PWM static converter, the SG acting as an idling motor is accelerated to the desired speed by a sensorless control system. The tested machine is vector controlled; thus, it is “in synchronism” at all speeds.

In contrast, when the power supply is a nearby SG, the tested SG is started either as an asynchronous motor or by accelerating the power supply generator simultaneously with the tested machine. Suppose that the SG was brought to rated speed and acts as a no-load motor. To segregate the no-load loss components, the idling motor is supplied with descending stator voltage and descending field current so

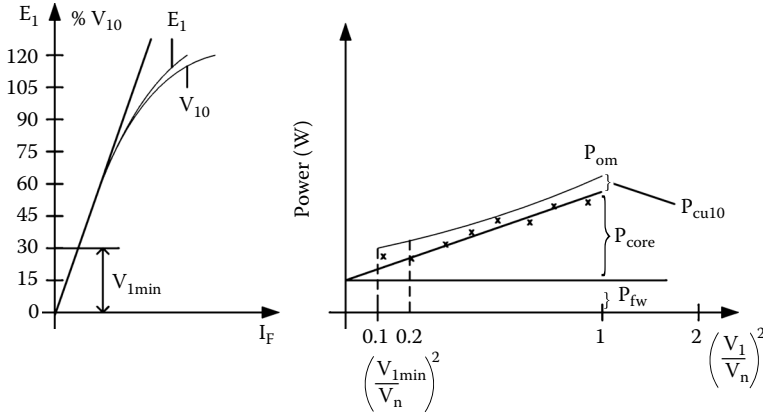


FIGURE 8.8 Loss segregation for idle-running motor testing.

as to keep unity power factor conditions (minimum stator current). The loss components of (input electric power) P_{om} are as follows:

$$P_{om} = P_{cu10} + P_{core} + P_{fw} \quad (8.14)$$

The stator winding loss P_{cu10} is

$$P_{cu10} = 3R_{adc} I_o^2 \quad (8.15)$$

and may be subtracted from the electric input P_{om} (Figure 8.8).

There is a minimum stator voltage V_{1min} , at unity power factor, for which the idling synchronous motor remains at synchronism. The difference $P_{om} - P_{cu10}$ is represented in Figure 8.8 as a function of voltage squared to underscore the core loss almost proportionally to voltage squared at given frequency (or to V/f in general). A straight line is obtained through curve fitting. This straight line is prolonged to the vertical axis, and thus, the mechanical loss P_{fw} is obtained. So, the P_{core} and P_{fw} were segregated. The open-circuit saturation curve may be obtained as a bonus (down to 30% rated voltage) by neglecting the voltage drop over the synchronous reactance (current is small) and over the stator resistance, which is even smaller. Moreover, if the synchronous reactance X_s (an “average” of X_d and X_q) is known from design data, at unity power factor, the no-load voltage (the electromagnetic field [emf] E_1) is

$$E_1 \approx \sqrt{(V_1 - R_a I_o^2)^2 + X_s^2 I_o^2} \quad (8.16)$$

The precision in E_1 is thus improved, and the obtained open-circuit saturation curve, $E_1(I_f)$, is more reliable. The initial 30% part of the open-circuit saturation curve is drawn as the airgap line (the tangent through origin to the measured open-circuit magnetic curve section). To determine the short-circuit and strayload losses, the idling motor is left to run at about 30% voltage (and at an even lower value, but for stable operation). By controlling the field current at this low, but constant, voltage, about six current step measurements are made from 125 to 25% of rated stator current. At least two points with very low stator current are also required. Again, total losses for this idling test are

$$(P_{om})_{lowvoltage} = P_{fw} + P_{core} + P_{cu1} + P_{strayload} \quad (8.17)$$

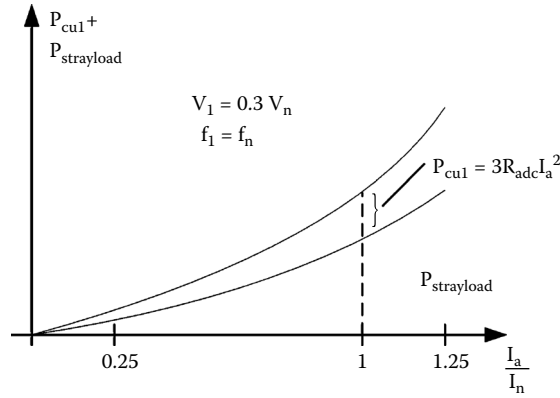


FIGURE 8.9 $P_{cu1} + P_{strayload}$.

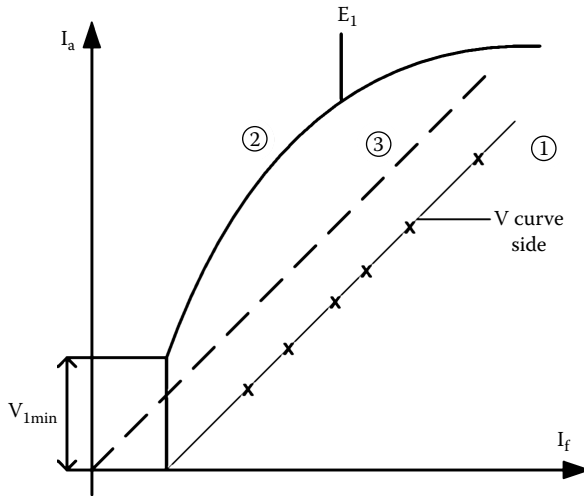


FIGURE 8.10 V curve at low voltage V_{1min} (1), open-circuit saturation curve (2), short-circuit saturation curve (3).

This time, the test is done at constant voltage, but the field current is decreased to increase the stator current up to 125%. So, the strayload losses become important. As the field current is reduced, the power factor decreases, so care must be exercised to measure the input electric power with good precision. As the P_{fw} loss is already known from the previous testing, speed is constant, P_{core} is known from the same source at the same low voltage at unity power factor conditions, and only $P_{core} + P_{strayload}$ have to be determined as a function of stator current.

Additionally, the dependence of I_a on I_f may be plotted from this low-voltage test (Figure 8.9). The intersection of this curve side with the abscissa delivers the field current that corresponds to the testing voltage V_{1min} on the open-circuit magnetization curve. The short-circuit saturation curve is just parallel to the V curve side $I_a(I_f)$ (see Figure 8.10).

We may conclude that both separate driving and electric power input tests allow for the segregation of all loss components in the machine and thus provide for the SG conventional efficiency computation:

$$\eta_c = \frac{P_1 - \sum P}{P_1}$$

$$\sum P = P_{fw} + P_{core} + P_{cul} \left(\frac{I_a}{I_n} \right)^2 + P_{strayload} \left(\frac{I_a}{I_n} \right)^2 + R_{fd} I_F^2 \quad (8.18)$$

The rated stator-winding loss P_{cul} and the rated stray-load loss $P_{strayload}$ are determined in short-circuit tests at rated current, while P_{core} is determined from the open-circuit test at rated voltage. It is disputable if the core losses calculated in the no-load test and strayload losses from the short-circuit test are the same when the SG operates on loads of various active and reactive power levels.

8.2.3 Retardation (Free Deceleration Tests)

In essence, after the SG operates as an uncoupled motor at steady state to reach normal temperatures, its speed is raised at 110% speed. Evidently, a separate SG supply capable of producing 110% rated frequency is required. Alternatively, a lower rated PWM converter may be used to supply the SG to slowly accelerate the SG as a motor. Then, the source is disconnected. The prime mover of the SG was decoupled or “dewatered.”

The deceleration tests are performed with $I_f, I_a = 0$, then with $I_f \neq 0, I_a = 0$ (open circuit), and, respectively, for $I_f = \text{constant}$, and $V_1 = 0$ (short-circuit). In the three cases, the motion equation leads to the following:

$$\begin{aligned} \frac{J \left(\frac{\omega_r}{p_1} \right) d\omega_r}{p_1 \left(\frac{\omega_r}{p_1} \right) dt} &= \frac{d}{dt} \left[\frac{J \left(\frac{\omega_r}{p_1} \right)^2}{2} \right] = -P_{fw}(\omega_r) \\ &= -P_{fw}(\omega_r) - P_{core}(\omega_r) \\ &= -P_{sc}(I_{sc3}) - P_{fw}(\omega_r) \end{aligned} \quad (8.19)$$

The speed vs. time during deceleration is measured, but its derivation with time has to be estimated through an adequate digital filter to secure a smooth signal.

Provided the inertia J is *a priori* known, at about rated speed, the speed ω_m and its derivative $d\omega_r/dt$ are acquired and used to calculate the losses for that rated speed, as shown on the right side of Equation 8.19 (Figure 8.11).

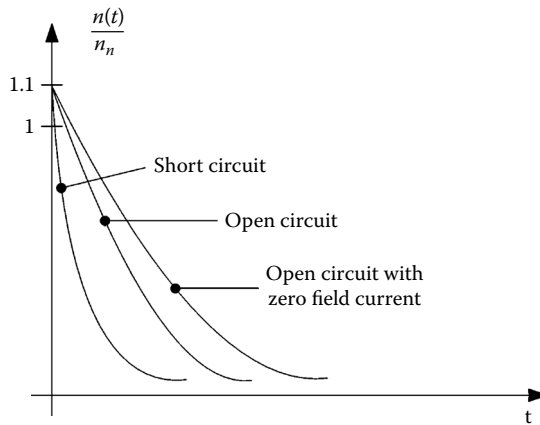


FIGURE 8.11 Retardation tests.

With the retardation tests done at various field current levels, respectively, at different values of short-circuit current, at rated speed, the dependence of $E_1(I_f)$, $P_{core}(I_f)$, and $P_{sc}(I_{sc3})$ may be obtained. Also,

$$P_{sc}(I_{sc3}) = 3R_{adc} I_{sc3}^2 + P_{strayload}(I_{sc3}) \quad (8.20)$$

In this way, the open-circuit saturation curve $E_1(I_f)$ is obtained, provided the terminal voltage is also acquired. Note that if the SG is excited from its exciter (brushless, in general), care must be exercised to keep the excitation current constant, and the exciter input power should be deducted from losses.

If overspeeding is not permitted, the data are collected at lower than rated speed with the losses corrected to rated speed (frequency). A tachometer, a speed recorder, or a frequency digital electronic detector may be used.

As already pointed out, the inertia J has to be known *a priori* for retardation tests. Inertia may be computed by using a number of methods, including through computation by manufacturer or from Equation 8.19, provided the friction and windage loss at rated speed $P_{fw}(\omega_{rn})$ are already known. With the same test set, the SG is run as an idling motor at rated speed and voltage for unity power factor (minimum current). Subtracting from input powers the stator winding loss, $P_{fw} + P_{core}$, corresponding to no load at the same field current, I_f is obtained. Then, Equation 8.19 is used again to obtain J . Finally, the physical pendulum method may be applied to calculate J (see IEEE standard 115-1995, paragraph 4.4.15).

For SGs with closed-loop water coolers, the calorimetric method may be used to directly measure the losses. Finally, the efficiency may be calculated from the measured output to measured input to SG. This direct approach is suitable for low- and medium-power SGs that can be fully loaded by the manufacturer to directly measure the input and output with good precision (less than 0.1 to 0.2%).

8.3 Excitation Current under Load and Voltage Regulation

The excitation (field) current required to operate the SG at rated steady-state active power, power factor, and voltage is a paramount factor in the thermal design of a machine.

Two essentially graphical methods — the Potier reactance and the partial saturation curves — were introduced in Chapter 7 on design. Here we will treat, basically, in more detail, variants of the Potier reactance method.

To determine the excitation current under specified load conditions, the Potier (or leakage) reactance X_p , the unsaturated d and q reactance X_{du} and X_{qu} , armature resistance R_a , and the open-circuit saturation curve are needed. Methods for determining the Potier and leakage reactance are given first.

8.3.1 The Armature Leakage Reactance

We can safely say that there is not yet a widely accepted (standardized) direct method with which to measure the stator leakage (reactance) of SGs. To the valuable heritage of analytical expressions for the various components of X_l (see Chapter 7), finite element method (FEM) calculation procedures were added [2, 3].

The stator leakage inductance may be calculated by subtracting two measured inductances:

$$L_l = L_{du} - L_{adu} \quad (8.21)$$

$$L_{adu} = L_{afdu} \cdot \frac{2}{3} \cdot \frac{1}{N_{af}} \quad ; \quad L_{afdu} = \frac{V_n \sqrt{2}}{\sqrt{3} \omega_n I_{fdbase}} \quad (8.22)$$

where L_{du} is the unsaturated axis synchronous inductance, and L_{adu} is the stator to field circuit mutual inductance reduced to the stator. L_{afdu} is the same mutual inductance but before reduction to stator. I_{fd} (base value) is the field current that produces, on the airgap straight line, the rated stator voltage on the open stator circuit. Finally, N_{af} is the field-to-armature equivalent turn ratio that may be extracted from design data or measured as shown later in this chapter.

The N_{af} ratio may be directly calculated from design data as follows:

$$N_{af} = \frac{3}{2} \frac{I_{abase} (A)}{i_{fd(base)} (A)} \quad ; \quad i_{fdbase} = I_{fdbase} \cdot L_{adu} \quad (8.23)$$

where i_{fdbase} , I_{fdbase} , and I_{abase} are in amperes, but L_{adu} is in P.U.

A method to directly measure the leakage inductance (reactance) is given in the literature [4]. The reduction of the Potier reactance when the terminal voltage increases is documented in Reference [4]. A simpler approach to estimate X_l would be to average homopolar reactance X_o and reactance of the machine without the rotor in place, X_{lair} :

$$X_l \approx \frac{(X_o + X_{lair})}{2} \quad (8.24)$$

In general, $X_o < X_l$ and $X_{lair} > X_p$, so an average of them seems realistic.

Alternatively,

$$X_l \approx X_{lair} - X_{air} \quad (8.25)$$

X_{air} represents the reactance of the magnetic field that is closed through the stator bore when the rotor is not in place. From two-dimensional field analysis, it was found that X_{air} corresponds to an equivalent airgap of τ/π (axial flux lines are neglected):

$$X_{air} = \frac{6\mu_o \omega_1 (W_1 k w_1)^2 \tau l_i}{\pi^2 p_1 (\tau/\pi)} \equiv \frac{\omega_1 L_{adu}}{K_{ad}} \cdot \left(\frac{g \pi K_c}{\tau} \right) \quad (8.26)$$

where

τ = the pole pitch

g = the airgap

l_i = the stator stack length

$K_{ad} = L_{adu}/L_{mu} > 0.9$ (see Chapter 7)

The measurement of X_o will be presented later in this chapter, while X_{lair} may be measured through a three-phase AC test at a low voltage level, with the rotor out of place. As expected, magnetic saturation is not present when measuring X_o and X_{lair} . In reality, for large values of stator currents and for very high levels of magnetic saturation of stator teeth or rotor pole, the leakage flux paths get saturated, and X_l slightly decreases. FEM inquiries [2, 3] suggest that such a phenomenon is notable.

When identifying the machine model under various conditions, a rather realistic, even though not exact, value of leakage reactance is *a priori* given. The above methods may serve this purpose well, as saturation will be accounted for through other components of the machine model.

8.3.2 The Potier Reactance

Difficulties in measuring the leakage reactance led, shortly after the year 1900, to an introduction by Potier of an alternative reactance (Potier reactance) that can be measured from the zero-power-factor

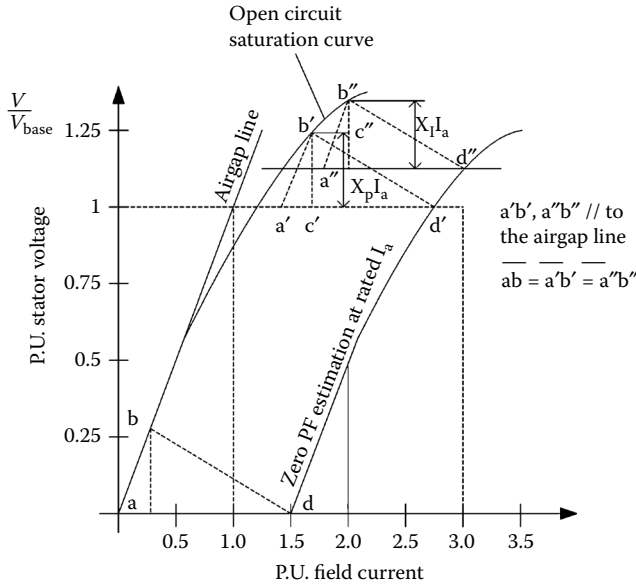


FIGURE 8.12 Potier reactance from zero power factor saturation curve.

load tests, at given stator voltage. At rated voltage tests, the Potier reactance X_p may be larger than the actual leakage reactance by as much as 20 to 30%.

The open-circuit saturation and zero-power-factor rated current saturation curves are required to determine the value of X_p (Figure 8.12).

At rated voltage level, the segment $a'd' = ad$ is marked. A parallel to the airgap line through a' intersects the open-circuit saturation curve at point b' . The segment $b'c'$ is as follows:

$$\overline{b'c'} = X_p I_a \quad (8.27)$$

It is argued that the value of X_p obtained at rated voltage level may be notably larger than the leakage reactance X_l , at least for salient-pole rotor SGs. A simple way to correct this situation is to apply the same method but at a higher level of voltage, where the level of saturation is higher, and thus, the segment $b''c'' < b'c'$ and $X'_p < X_p$ and, approximately,

$$X_l \approx X'_p \approx \frac{\overline{b''c''}}{I_a} \quad (8.28)$$

It is not yet clear what overvoltage level can be considered, but less than 110% is feasible if the SG may be run at such overvoltage without excessive overheating, even if only for obtaining the zero-power-factor saturation curve up to 110%.

When the synchronous machine is operated as an SG on full load, other methods to calculate X_p from measurements are applicable [1].

8.3.3 Excitation Current for Specified Load

The excitation field current for specified electric load conditions (voltage, current, power factor) may be calculated by using the phasor diagram (Figure 8.13).

For given stator current I_a , terminal voltage E_a , and power factor angle ϕ , the power angle δ may be calculated from the phasor diagram as follows:

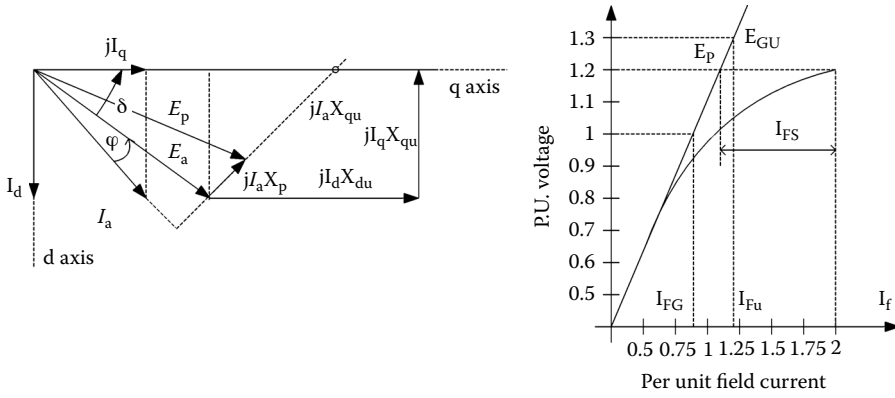


FIGURE 8.13 Phasor diagram with unsaturated reactances X_{du} and X_{qu} and the open-circuit saturation curve. E_a is the terminal phase voltage; δ is the power angle; I_a is the terminal phase current; φ is the power factor angle; E_{as} is the voltage back of X_{qu} ; R_a is the stator phase resistance; and E_{Gu} is the voltage back of X_{du} .

$$\delta = \tan^{-1} \left[\frac{I_a R_a \sin \varphi + I_a X_{qu} \cos \varphi}{E_a + I_a R_a \cos \varphi + I_a X_{qu} \sin \varphi} \right] \quad (8.29)$$

$$I_d = I_a \sin(\delta + \varphi) \quad ; \quad I_q = I_a \cos(\delta + \varphi) \quad (8.30)$$

Once the power angle is calculated, for given unsaturated reactances X_{du} , X_{qu} and stator resistance, the computation of voltages E_{QD} and E_{Gu} , with the machine considered as unsaturated, is feasible:

$$\underline{E}_{Gu} = E_a + R_s I_a + jI_q X_{qu} + jX_d X_{du} \quad (8.31)$$

$$E_{Gu} = (E_a + R_a I_a) \cos \delta + X_{du} I_a \sin(\delta + \varphi) \quad (8.32)$$

Corresponding to E_{Gu} , from the open-circuit saturation curve (Figure 8.13), the excitation current I_{FU} is found. The voltage back of Potier reactance E_p is simply as follows (Figure 8.13):

$$\begin{aligned} \underline{E}_p &= \underline{E}_a + R_s \underline{I}_a + jX_p \underline{I}_a \\ E_p &= \sqrt{(E_a \sin \varphi + I_a X_p)^2 + (E_a \cos \varphi + I_a R_a)^2} \end{aligned} \quad (8.33)$$

The excitation current under saturated conditions that produces E_p along the open-circuit saturation curve, is as follows (Figure 8.13):

$$I_F = I_{Fu} + I_{FS} \quad (8.34)$$

The “saturation” field current supplement is I_{FS} . The field current I_F corresponds to the saturated machine and is the excitation current under specified load. This information is crucial for the thermal design of SG. The procedure is similar for the cylindrical rotor machine, where the difference between X_{du} and X_{qu} is small (less than 10%). For variants of this method see Reference [1].

All methods in Reference [1] have in common a critical simplification: the magnetic saturation influence is the same in axes d and q , while the power angle δ calculated with unsaturated reactance X_{qu}

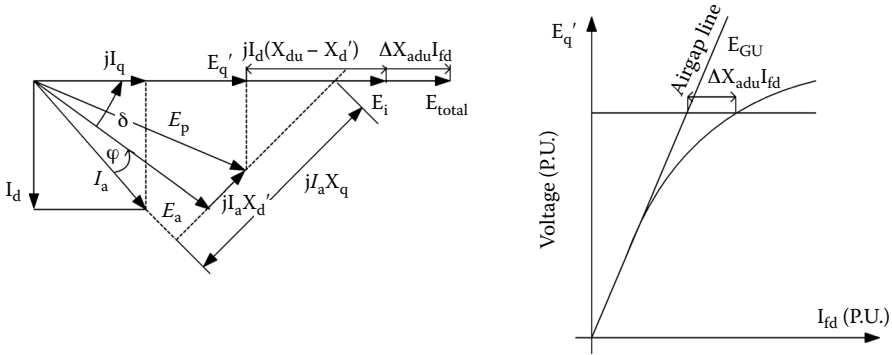


FIGURE 8.14 The transient model phasor diagram.

is considered to hold for all load conditions. The reality of saturation is much more complicated, but these simplifications are still widely accepted, as they apparently allowed for acceptable results so far.

The consideration of different magnetization curves along axes d and q , even for cylindrical rotors, and the presence of cross-coupling saturation were discussed in Chapter 7 on design, via the partial magnetization curve method. This is not the only approach to the computation of excitation current under load in a saturated SG, and new simplified methods to account for saturation under steady state are being produced [5].

8.3.4 Excitation Current for Stability Studies

When investigating stability, the torque during transients is mandatory. Its formula is still as follows:

$$T_e = \Psi_d I_q - \Psi_q I_d \quad (8.35)$$

When damping windings effects are neglected, the transient model and phasor diagram may be used, with X_d' replacing X_d , while X_q holds steady (Figure 8.14).

As seen from Figure 8.14, the total open-circuit voltage E_{total} , which defines the required field current I_{ftotal} , is

$$E_{total} = E_q' + (X_{du} - X_d') I_d + X_{adu} I_{fd} \quad (8.36)$$

$$E_q' = E_a \cos \delta + I_a X_d' \sin(\delta + \phi) \quad (8.37)$$

This time, at the level of E_q' (rather than E_p), the saturation increment in excitation (in P.U.), $\Delta X_{adu} * I_{fd}$, is determined from the open-circuit saturation curve (Figure 8.14). The nonreciprocal system (Equation 8.23) is used in P.U. It is again obvious that the difference in saturation levels in the d and q axes is neglected. The voltage regulation is the relative difference between the no-load voltage E_{total} (Figure 8.14) corresponding to the excitation current under load, and the SG rated terminal voltage E_{an} :

$$\text{voltage regulation} = \frac{E_{total}}{E_{an}} - 1 \quad (8.38)$$

8.3.5 Temperature Tests

When determining the temperature rise of various points in an SG, it is crucial to check its capability to deliver load power according to specifications. The temperature rise is calculated with respect to a

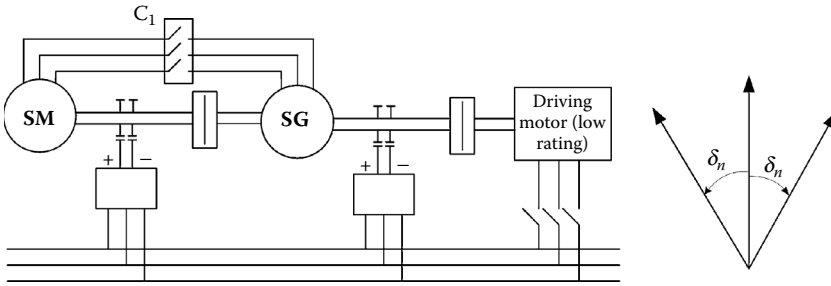


FIGURE 8.15 Back-to-back loading.

reference temperature. Coolant temperature is now a widely accepted reference temperature. A temperature rise at one (rated) or more specified load levels is required from temperature tests. When possible, direct loading should be applied to do temperature testing, either at the manufacturer's or at the user's site. Four common temperature testing methods are described here:

- Conventional (direct) loading
- Synchronous feedback (back-to-back motor [M] + generator [G]) loading
- Zero-power-factor load test
- Open-circuit and short-circuit loading

8.3.5.1 Conventional Loading

The SG is loaded for specified conditions of voltage, frequency, active power, armature current, and field current (the voltage regulator is disengaged). The machine terminal voltage should be maintained within $\pm 2\%$ of rated value. If so, the temperature increases of different parts of the machine may be plotted vs. P.U. squared apparent power (MVA)². As the voltage-dependent and current-dependent losses are generally unequal, the stator-winding temperature rise may be plotted vs. armature current squared (A²), while the field-winding temperature can be plotted vs. field-winding dissipated power: $P_{exc} = R_F i_F^2$ (kW). Linear dependencies are expected. If temperature testing is to be done before commissioning the SG, then the last three methods listed above are to be used.

8.3.5.2 Synchronous Feedback (Back-to-Back) Loading Testing

Two identical SGs are coupled together with their rotor axes shifted with respect to each other by twice the rated power angle ($2\delta_n$). They are driven to rated speed before connecting their stators (C_1 -open) (Figure 8.15).

Then, the excitation of both machines is raised until both SMs show the same rated voltage. With the synchronization conditions met, the power switch C_1 is closed. Further on, the excitation of one of the two identical machines is reduced. That machine becomes a motor and the other a generator. Then, simultaneously, SM excitation current is reduced and that of the SG is increased to keep the terminal voltage at rated value. The current between the two machines increases until the excitation current of the SG reaches its rated value, by now known for rated power, voltage, $\cos \phi$. The speed is maintained constant through all these arrangements. The net output power of the driving motor covers the losses of the two identical synchronous machines, $2\Sigma_p$, but the power exchanged between the two machines is the rated power P_n and can be measured. So, even the rated efficiency can be calculated, besides offering adequate loading for temperature tests by taking measurements every half hour until temperatures stabilize.

Two identical machines are required for this arrangement, along with the lower (6%) rating driving motor and its coupling. It is possible to use only the SM and SG, with SM driving the set, but then the local power connectors have to be sized to the full rating of the tested machines.

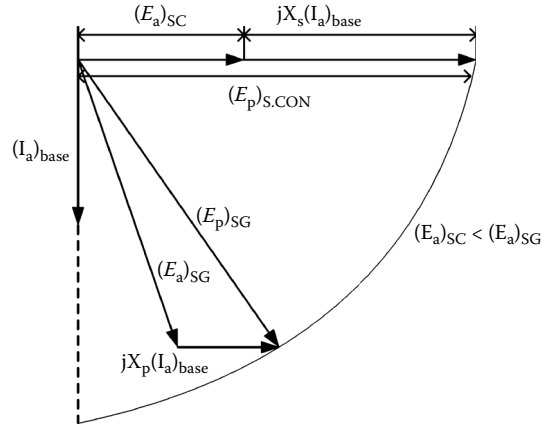


FIGURE 8.16 Equalizing the voltage back of Potier reactance for synchronous condenser and synchronous generator operation modes.

8.3.5.3 Zero-Power-Factor Load Test

The SG works as a synchronous motor uncoupled at the shaft, that is, a synchronous condenser (S.CON). As the active power drawn from the power grid is equal to SM losses, the method is energy efficient. There are, however, two problems:

- Starting and synchronizing the SM to the power source
- Making sure that the losses in the S.CON equal the losses in the SG at specified load conditions

Starting may be done through an existing SG supply that is accelerated in the same time with the SM, up to the rated speed. A synchronous motor starting may be used instead. To adjust the stator winding, core losses, and field-winding losses, for a given speed, and to provide for the rated mechanical losses, the supply voltage $(E_a)_{S.CON}$ and the field current may be adjusted.

In essence, the voltage $(E_p)_{S.CON}$ has to provide the same voltage behind Potier reactance with the S.CON as with the voltage E_a of SG at a specified load (Figure 8.16):

$$(E_p)_{S.CON} = (E_p)_{SG} \quad (8.39)$$

There are two more problems with this otherwise good test method for heating. One problem is the necessity of the variable voltage source at the level of the rated current of the SG. The second is related to the danger of too high a temperature in the field winding in SGs designed for larger than 0.9 rated power factor. The high level of E_p in the SG tests claims too large a field current (larger than for the rated load in the SG design).

Other adjustments have to be made for refined loss equivalence, such that the temperature rise is close to that in the actual SG at specified (rated load) conditions.

8.3.5.4 Open-Circuit and Short-Circuit “Loading”

As elaborated upon in [Chapter 7](#) on design, the total loss of the SG under load is obtained by adding the open-circuit losses at rated voltage and the short-circuit loss at rated current and correcting for duplication of heating due to windage losses.

In other words, the open-circuit and short-circuit tests are done sequentially, and the overtemperatures $\Delta t_t = (\Delta t)_{open\ circuit}$ and Δt_{sc} are added, while subtracting the additional temperature rise due to duplication of mechanical losses Δt_w :

$$\Delta t_t = (\Delta t)_{\text{open circuit}} + (\Delta t)_{\text{short circuit}} - (\Delta t)_w \quad (8.40)$$

The temperature rise $(\Delta t)_w$ due to windage losses may be determined by a zero excitation open-circuit run. For more details on practical temperature tests, see Reference [1].

8.4 The Need for Determining Electrical Parameters

Prior to the period from 1945 to 1965, SG transient and subtransient parameters were developed and used to determine balanced and unbalanced fault currents. For stability response, a constant voltage back-transient reactance model was applied in the same period.

The development of power electronics controlled exciters led, after 1965, to high initial excitation response. Considerably more sophisticated SG and excitation control systems models became necessary. Time-domain digital simulation tools were developed, and small-signal linear eigenvalue analysis became the norm in SG stability and control studies. Besides second-order (two rotor circuits in parallel along each orthogonal axis) SG models, third and higher rotor order models were developed to accommodate the wider frequency spectrum encountered by some power electronics excitation systems. These practical requirements led to the IEEE standard 115A-1987 on standstill frequency testing to deal with third rotor order SG model identification.

Tests to determine the SG parameters for steady states and for transients were developed and standardized since 1965 at a rather high pace. Steady-state parameters — X_d , unsaturated (X_{du}) and saturated (X_{ds}), and X_q , unsaturated (X_{qu}) and saturated (X_{qs}) — are required first in order to compute the active and reactive power delivered by the SG at given power angle, voltage, armature current, and field current.

The field current required for given active, reactive powers, power factor, and voltage, as described in previous paragraphs, is necessary in order to calculate the maximum reactive power that the SG can deliver within given (rated) temperature constraints. The line-charging maximum-absorbed reactive power of the SG at zero power factor (zero active power) is also calculated based on steady-state parameters.

Load flow studies are based on steady-state parameters as influenced by magnetic saturation and temperature (resistances R_a and R_f). The subtransient and transient parameters (X_d'' , X_d' , T_d'' , T_d' , X_q'' , X_q' , T_{d0}'' , T_{d0}' , T_{q0}''), determined by processing the three-phase short-circuit tests, are generally used to study the power system protection and circuit-breaker fault interruption requirements. The magnetic saturation influence on these parameters is also needed for better precision when they are applied at rated voltage and higher current conditions. Empirical corrections for saturation are still the norm.

Standstill frequency response (SSFR) tests are mainly used to determine third-order rotor model sub-subtransient, subtransient, and transient reactances and time constraints at low values of stator current (0.5% of rated current). They may be identified through various regression methods, and some have been shown to fit well the SSFR from 0.001 Hz to 200 Hz. Such a broad frequency spectrum occurs in very few transients. Also, the transients occur at rather high and variable local saturation levels in the SG.

In just how many real-life SG transients are such advanced SSFR methods a must is not yet very clear. However, when lower frequency band response is required, SSFR results may be used to produce the best-fit transient parameters for that limited frequency band, through the same regression methods.

The validation of these advanced third (or higher) rotor order models in most important real-time transients led to the use of similar regression methods to identify the SG transient parameters from online admissible (provoked) transients. Such a transient is a 30% variation of excitation voltage. Limited frequency range oscillations of the exciter's voltage may also be performed to identify SG models valid for on-load transients, *a posteriori*.

The limits of short-circuit tests or SSFR taken separately appear clearly in such situations, and their combination to identify SG models is one more way to better the SG modeling for on-load transients. As all parameter estimation methods use P.U. values, we will revisit them here in the standardized form.

8.5 Per Unit Values

Voltages, currents, powers, torque, reactances, inductances, and resistances are required, in general, to be expressed in per unit (P.U.) values with the inertia and time constants left in seconds. Per-unitization has to be consistent. In general, three base quantities are selected, while the others are derived from the latter. The three commonly used quantities are three-phase base power, $S_{N\Delta}$, line-to-line base terminal voltage $E_{N\Delta}$, and base frequency, f_N .

To express a measurable physical quantity in P.U., its physical value is divided by the pertinent base value expressed in the same units. Conversion of a P.U. quantity to a new base is done by multiplying the old P.U. value by the ratio of the old to the new base quantity. The three-phase power $S_{N\Delta}$ of an SG is taken as its rated kilovoltampere (kVA) (or megavoltampere [MVA]) output (apparent power).

The single-phase base power S_N is $S_N = S_{N\Delta}/3$.

Base voltage is the rated line-to-neutral voltage E_N :

$$E_N = \frac{E_{N\Delta}}{\sqrt{3}} \quad (\text{V,kV}) \quad ; \quad E_{N\Delta} = E_{LL} \quad (8.41)$$

RMS quantities are used.

When sinusoidal balanced operation is considered, the P.U. value of the line-to-line and of the phase-neutral voltages is the same. Baseline current I_N is that value of stator current that corresponds to rated (base) power at rated (base) voltage:

$$I_N = \frac{S_{N\Delta}}{\sqrt{3}V_{N\Delta}} = \frac{S_N}{E_N} \quad (\text{A}) \quad ; \quad S_N = S_{N\Delta}/3 \quad (8.42)$$

For delta-connected SGs, the phase base current $I_{N\Delta}$ is as follows:

$$I_{N\Delta} = \frac{S_{N\Delta}}{3E_{N\Delta}} \quad \text{as } E_{N\Delta} = E_N \quad (8.43)$$

The base impedance Z_N is

$$Z_N = \frac{E_N}{I_N} = \frac{E_N^2}{S_N} = \frac{E_{N\Delta}^2}{S_{N\Delta}} \quad (8.44)$$

The base impedance corresponds to the balanced load phase impedance at SG terminals that requires the rated current I_N at rated (base) line to neutral (base) voltage E_N . Note that, in some cases, the field-circuit-based impedance Z_{fbase} is defined in a different way (Z_N is abandoned for the field-circuit P.U. quantities):

$$Z_{fbase} = \frac{S_{N\Delta}}{(I_{fbase})^2} = \frac{3S_N}{(I_{fbase})^2} \quad (8.45)$$

I_{fbase} is the field current in amperes required to induce, at stator terminals, on an open-circuit straight line, the P.U. voltage E_a :

$$E_a(\text{P.U.}) = X_{adu}(\text{P.U.}) I_a(\text{P.U.}) \quad (8.46)$$

where

I_a = the P.U. value of stator current I_N

X_{adu} = the mutual P.U. reactance between the armature winding and field winding on the base Z_N

In general,

$$X_{du} = X_{adu} + X_l \quad (8.47)$$

where

X_{du} = the unsaturated d axis reactance

X_l = the leakage reactance

The direct addition of terms in Equation 8.47 indicates that X_{adu} is already reduced to the stator. Rankin [6] designated $i_{fd\text{base}}$ as the reciprocal system.

In the conventional (nonreciprocal) system, the base current of the field winding $I_{fd\text{base}}$ corresponds to the 1.0 P.U. volts E_a on an open-circuit straight line:

$$i_{fd\text{base}} = I_{fd\text{base}} X_{adu} \quad (8.48)$$

The Rankin's system is characterized by equal stator/field and field/stator mutual reactances in P.U. values.

The correspondence between $i_{fd\text{base}}$ and $I_{fd\text{base}}$ is shown graphically in Figure 8.17.

All rotor quantities, such as field-winding voltage, reactance, and resistance, are expressed in P.U. values according to either the conventional ($I_{fd\text{base}}$) or to the reciprocal ($i_{fd\text{base}}$) field current base quantity.

The base frequency is the rated frequency f_N . Sometimes, the time also has a base value $t_N = 1/f_N$. The theoretical foundations and the definitions behind expressions of SG parameters for steady-state and transient conditions were described in Chapter 5 and Chapter 6. Here, they will be recalled at the moment of utilization.

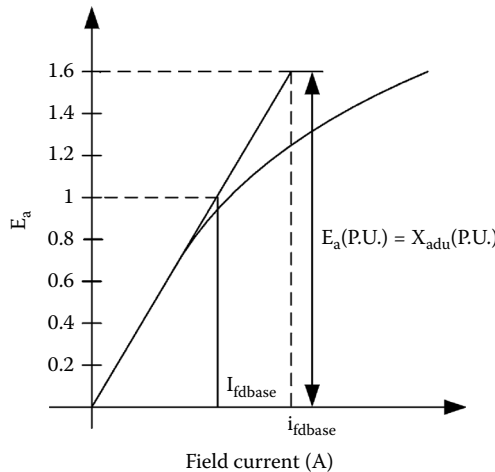


FIGURE 8.17 $I_{fd\text{base}}$ and $i_{fd\text{base}}$ base field current definitions.

8.6 Tests for Parameters under Steady State

Steady-state operation of a three-phase SG usually takes place under balanced load conditions. That is, phase currents are equal in amplitude but dephased by 120° with each other. There are, however, situations when the SG has to operate under unbalanced steady-state conditions. As already detailed in [Chapter 5](#) (on steady-state performance), unbalanced operation may be described through the method of symmetrical components. The steady-state reactances X_d , X_q , or X_l , correspond to positive symmetrical components: X_2 for the negative and X_o for the zero components. Together with direct sequence parameters for transients, X_2 and X_o enter the expressions of generator current under unbalanced transients.

In essence, the tests that follow are designed for three-phase SGs, but with some adaptations, they may also be used for single-phase generators. However, this latter case will be treated separately in Chapter 12 in *Variable Speed Generators*, on small power single-phase linear motion generators.

The parameters to be measured for steady-state modeling of an SG are as follows:

- X_{du} is the unsaturated direct axis reactance
- X_{ds} is the saturated direct axis reactance dependent on SG voltage, power (in MVA), and power factor
- X_{adu} is the unsaturated direct axis mutual (stator to excitation) reactance already reduced to the stator ($X_{du} = X_{adu} + X_l$)
- X_l is the stator leakage reactance
- X_{ads} is the saturated (main flux) direct axis magnetization reactance ($X_{ds} = X_{ads} + X_l$)
- X_{qu} is the unsaturated quadrature axis reactance
- X_{qs} is the saturated quadrature axis reactance
- X_{aqs} is the saturated quadrature axis magnetization reactance
- X_2 is the negative sequence resistance
- X_o is the zero-sequence reactance
- R_o is the zero-sequence resistance
- SCR is the short-circuit ratio ($1/X_{du}$)
- δ is the internal power angle in radians or electrical degrees

All resistances and reactances above are in P.U.

8.6.1 X_{du} , X_{ds} Measurements

The unsaturated direct axis synchronous reactance X_{du} (P.U.) can be calculated as a ratio between two field currents:

$$X_{du} = \frac{I_{FSI}}{I_{FG}} \quad (8.49)$$

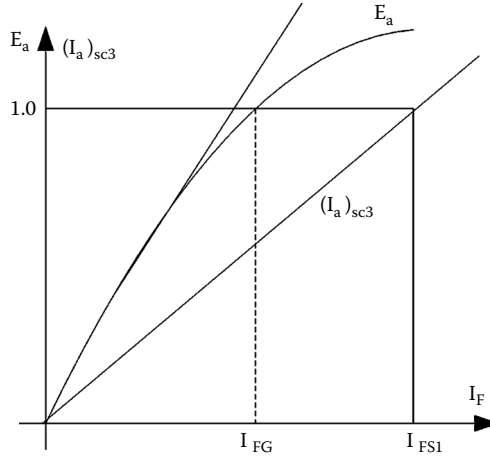
where

I_{FSI} = the field current on the short-circuit saturation curve that corresponds to base stator current
 I_{FG} = the field current on the open-loop saturation curve that holds for base voltage on the airgap line ([Figure 8.18](#))

Also,

$$X_{du} = X_{adu} + X_l \quad (8.50)$$

When saturation occurs in the main flux path, X_{adu} is replaced by its saturated value X_{ads} :

FIGURE 8.18 X_{du} calculation.

$$X_{ds} = X_{ads} + X_l \quad (8.51)$$

As for steady state, the stator current in P.U. is not larger than 1.2 to 1.3 (for short time intervals), the leakage reactance X_p , still to be considered constant through its differential component, may vary with load conditions, as suggested by recent FEM calculations [2, 3].

8.6.2 Quadrature-Axis Magnetic Saturation X_q from Slip Tests

It is known that magnetic saturation influences X_q and, in general,

$$X_{qs} = X_{aqs} + X_l \quad ; \quad X_{qu} = X_{aqu} + X_l \quad (8.52)$$

The slip tests and the maximum lagging current test are considered here for X_q measurements.

8.6.2.1 Slip Test

The SG is driven at very low slip (very close to synchronism) with open field winding. The stator is fed from a three-phase power source at rated frequency. The slip is the ratio of the frequency of the emf of the field winding to the rated frequency. A low-voltage spark gap across the field-winding terminal would protect it from too high accidental emfs. The slip has to be very small to avoid speed pulsations due to damper-induced currents. The SG will pass from positions in direct to positions in quadrature axes, with variations in power source voltage E_a and current I_a from $(E_{\max}, I_{a\min})$ to $(E_{\min}, I_{a\max})$:

$$X_q = \frac{E_{a\min}}{I_{a\max}} \quad ; \quad X_d = \frac{E_{a\max}}{I_{a\min}} \quad (8.53)$$

The degree of saturation depends on the level of current in the machine. To determine the unsaturated values of X_d and X_q , the voltage of the power source is reduced, generally below 60% of base value V_N .

In principle, at rated voltage, notable saturation occurs, which at least for axis q may be calculated as function of I_q with $I_q = I_{a\max}$. In axis d the absence of field current makes X_d ($I_d = I_{a\min}$) less representative, though still useful, for saturation consideration.

8.6.2.2 Quadrature Axis (Reactance) X_q from Maximum Lagging Current Test

The SG is run as a synchronous motor with no mechanical load at open-circuit rated voltage field current I_{FG} level, with applied voltages E_a less than 75% of base value E_N . Subsequently, the field current is reduced to zero and reversed in polarity and increased again in small increments with the opposite polarity. During this period of time, the armature current increases slowly until instability occurs at I_{as} . When the field current polarity is changed, the electromagnetic torque (in phase quantities) becomes

$$T_e = 3p_1(\Psi_d i_q - \Psi_q i_d) = 3p_1[-X_{ad}I_F + (X_d - X_q)i_d]i_q \quad (8.54)$$

The ideal maximum negative field current I_F that produces stability is obtained for zero torque:

$$I_F = (X_d - X_q) \cdot i_d / X_{ad} \quad (8.55)$$

The flux linkages are now as follows:

$$\Psi_d \approx \frac{X_{ad}I_F}{\omega_1} + \frac{X_d}{\omega_1}I_{as} \quad (8.56)$$

With Equation 8.55, Equation 8.56 becomes as follows:

$$\Psi_d = \frac{X_q}{\omega_1}I_{as} \quad ; \quad \Psi_q = \frac{X_q}{\omega_1}I_q \approx 0 \quad (8.57)$$

The phase voltage E_a is

$$E_a = \omega_1 \Psi_s = \omega_1 \Psi_d = X_q I_{as} \quad (8.58)$$

See also [Figure 8.19](#).

Finally,

$$X_q \approx \frac{E_a}{I_{as}} \quad (8.59)$$

Though the expression of X_q is straightforward, running the machine as a motor on no-load is not always feasible. Synchronous condensers, however, are a typical case when such a situation occurs naturally. There is some degree of saturation in the machine, but this is mainly due to d axis magnetizing magnetomotive forces (mmfs; produced by excitation plus the armature reaction). Catching the situation when stability is lost requires very small and slow increments in I_F , which requires special equipment.

8.6.3 Negative Sequence Impedance Z_2

Stator current harmonics may change the fundamental negative sequence voltage, but without changes in the fundamental negative sequence current. This phenomenon is more pronounced in salient motor pole machines with an incomplete damper ring or without damper winding, because there is a difference between subtransient reactances X_d'' and X_q'' .

Consequently, during tests, sinusoidal negative sequence currents have to be injected into the stator, and the fundamental frequency component of the negative sequence voltage has to be measured for

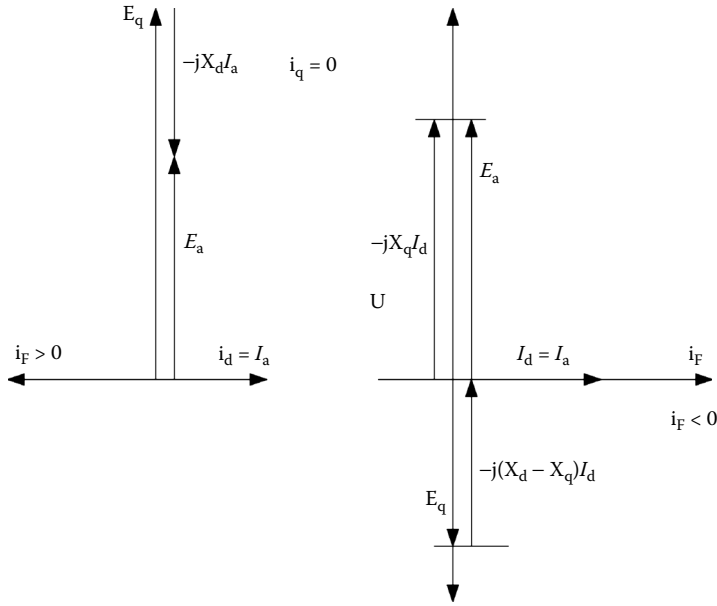


FIGURE 8.19 Phasor diagram for the maximum lagging current tests.

correct estimation of negative sequence impedance Z_2 . In general, corrections of the measured Z_2 are operated based on a known value of the subtransient reactance X_d'' .

The negative sequence impedance is defined for a negative sequence current equal to rated current. A few steady-state methods to measure X_2 are given here.

8.6.3.1 Applying Negative Sequence Currents

With the field winding short-circuited, the SG is driven at synchronous (rated) speed while being supplied with negative sequence currents in the stator at frequency f_N . Values of currents around rated current are used to run a few tests and then to claim an average Z_2 by measuring input power current and voltage.

To secure sinusoidal currents, with a voltage source, linear reactors are connected in series. The waveform of one stator current should be analyzed. If current harmonics content is above 5%, the test is prone to appreciable errors. The parameters extracted from measuring power, P , voltage (E_a), and current I_a , per phase are as follows:

$$Z_2 = \frac{E_a}{I_a} \quad \text{negative sequence impedance} \quad (8.60)$$

$$R_2 = \frac{P}{I_a^2} \quad \text{negative sequence resistance} \quad (8.61)$$

$$X_2 = \sqrt{Z_2^2 - R_2^2} \quad \text{negative sequence reactance} \quad (8.62)$$

8.6.3.2 Applying Negative Sequence Voltages

This is a variant of the above method suitable for salient-pole rotor SGs that lack damper windings. This time, the power supply has a low impedance to provide for sinusoidal voltage. Eventual harmonics in current or voltage have to be checked and left aside. Corrections to the above value are as follows [1]:

$$X_{2c} = \frac{(X'_d)^2}{(2X'_d - X_2)} \quad (8.63)$$

8.6.3.3 Steady-State Line-to-Line Short-Circuit Tests

As shown in [Chapter 4](#), during steady-state line-to-line short-circuit at rated speed, the voltage of the open phase (E_a) is as follows:

$$(E_a)_{\text{openphase}} = \frac{2}{\sqrt{3}} Z_2 I_{sc2} \quad (8.64)$$

Harmonics are eliminated from both I_{sc2} and $(E_a)_{\text{openphase}}$. Their phase shift ϕ_{os} is measured:

$$Z_2 = \frac{E_a \sqrt{3}}{2I_{sc2}} ; R_2 = Z_2 \cos \phi_{os} \quad (8.65)$$

When the stator null point of the windings is not available, the voltage E_{ab} is measured (bc line short-circuit). Also, the phase shift ϕ_{osc} between E_{ab} and I_{sc2} is measured. Consequently,

$$Z_2 = \frac{E_{ab}}{\sqrt{3}I_{sc2}} \quad \text{in } (\Omega) ; R_2 = Z_2 \cos \phi_{osc} \quad (8.66)$$

The presence of the third harmonic in the short-circuit current needs to be addressed [1]. The corrected X_{2c} value of X_2 is

$$X_{2sc} = \frac{X_2^2 + (X'_d)^2}{2X'_d} \quad (8.67)$$

Both X_2 and X_d'' have to be determined at rated current level. With both E_{ab} and I_{sc2} waveforms acquired during sustained short-circuit tests, only the fundamentals are retained by post-processing; thus, Z_2 and R_2 are determined with good precision.

8.6.4 Zero Sequence Impedance Z_o

With the SG at standstill, and three phases in parallel ([Figure 8.20a](#)) or in series ([Figure 8.20b](#)), the stator is AC supplied from a single-phase power source. The same tests may also be performed at rated speed.

As an alternative to taking phase-angle ϕ_o measurements, the input power P_a may be measured:

$$Z_o = \frac{3E_a}{I_a} \quad \text{for parallel connection} \quad (8.68)$$

$$R_o = \frac{3P_o}{I_a^2} \quad \text{for parallel connection} \quad (8.69)$$

$$Z_o = \frac{E_a}{3I_a} \quad \text{for series connection} \quad (8.70)$$

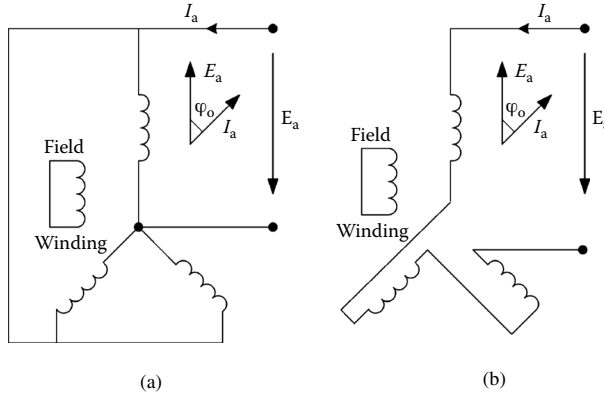


FIGURE 8.20 Single-phase supply tests to determine Z_o .

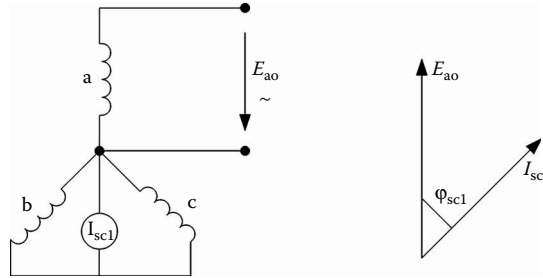


FIGURE 8.21 Sustained two line-to-neutral short-circuit.

$$R_o = \frac{P_o}{3I_a^2} \quad \text{for series connection} \quad (8.71)$$

Alternatively,

$$R_o = Z_o \cos \phi_o \quad X_o = \sqrt{Z_o^2 - R_o^2} \quad (8.72)$$

Among other methods to determine Z_o , we mention here the two line-to-neutral sustained short-circuit (Figure 8.21) methods with the machine at rated speed.

The zero sequence impedance Z_o is simply

$$Z_o = \frac{E_{a0}}{I_{sc1}} \quad (8.73)$$

$$R_o = Z_o \cos \phi_{sc1}; \quad X_o = \sqrt{Z_o^2 - R_o^2} \quad (8.74)$$

In this test, the zero sequence current is, in fact, one third of the neutral current I_{sc1} . As Z_o is a small quantity, care must be exercised to reduce the influence of power, voltage, or current devices and of the leads in the measurements for medium and large power SGs.

8.6.5 Short-Circuit Ratio

The SCR is obtained from the open-circuit and short-circuit saturation curves and is defined as in IEEE standard 100-1992:

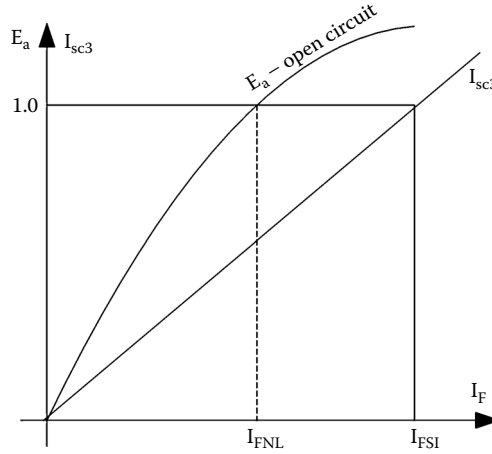


FIGURE 8.22 Extracting the short-circuit ratio (SCR).

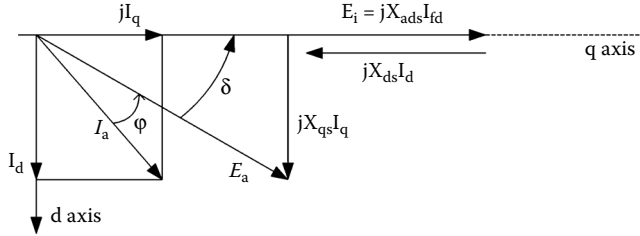


FIGURE 8.23 Phasor diagram for zero losses.

$$SCR = \frac{I_{FNL}}{I_{FSI}} \approx \frac{1}{X_d} \quad (\text{P.U.}) \quad (8.75)$$

where

I_{FNL} = the field current from the open-circuit saturation curve corresponding to rated voltage at rated frequency

I_{FSI} = the field current for rated armature current from the three-phase short-circuit saturation curve at rated frequency (Figure 8.22)

Though there is some degree of saturation considered in the SCR, it is by no means the same as for rated load conditions; this way, SCR is only a qualitative performance index, required for preliminary design (see Chapter 7).

8.6.6 Angle δ , X_{ds} , X_{qs} Determination from Load Tests

The load angle δ is defined as the angular displacement of the center line of a rotor pole field axis from the axis of stator mmf wave (space vector), for a specified load. In principle δ , may also be measured during transients. When iron loss is neglected δ is the angle between the field-current-produced emf and the phase voltage E_a , as apparent from the phasor diagram (Figure 8.23).

With the machine loaded, if the load angle δ is measured directly by a separate sensor, the steady-state load measurements may be used to determine the steady-state parameters X_{ds} and X_{qs} , with known leakage reactance X_l ($X_{ds} = X_{ads} + X_l$) (Figure 8.21). The load angle δ may be calculated as follows:

$$\delta = \tan^{-1} \left(\frac{I_a X_{qs} \cos \varphi}{E_a + I_a X_{qs} \sin \varphi} \right) \quad (8.76)$$

As δ , I_a , E_a , and φ are measured directly, the saturated reactance X_{qs} may be calculated directly for the actual saturation conditions. The I_d , I_q current components are available:

$$I_d = I_a \sin(\varphi + \delta) \quad (8.77)$$

$$I_q = I_a \cos(\varphi + \delta) \quad (8.78)$$

Also, from [Figure 8.21](#),

$$X_{ads} I_{fd} - (X_{ads} + X_l) I_d = E_a \cos \delta \quad (8.79)$$

As the leakage reactance X_l is considered already known, I_{fd} , E_a , and δ are measured directly (after reduction to stator); I_d is obtained from Equation 8.77; and Equation 8.79 yields the saturated value of the direct-axis reactance $X_{ds} = X_l + X_{ads}$. The load angle may be measured by encoders, by resolvers, or by electronic angle shifting measuring devices [1].

The reduction factor of the directly measured excitation current to the stator from I_f to I_{fd} may be taken from design data or calculated from SSFR tests as shown later in this chapter. If load tests are performed for different currents and power factor angles at constant voltage (P and Q) and δ , I_a , $\cos \varphi$, and I_{fd} are measured, families of curves $X_{ads}(I_d + I_{fd}, I_q)$ and $X_{qs}(I_q, I_d + I_{fd})$ are obtained. Alternatively, the $\Psi_d(I_q, I_d + I_{fd})$ and $\Psi_q(I_q, I_d + I_{fd})$ curve family is obtained:

$$\Psi_d = X_l i_d + X_{ads}(i_d + i_{fd}) \quad (8.80)$$

$$\Psi_q = X_{qs} i_q \quad (8.81)$$

Based on such data, curve-fitting functions may be built. Same data may be obtained from FEM calculations. Such a confrontation between FEM and direct tests for steady-state parameter saturation curve families ([Figure 8.24](#)) for online large SGs is still awaited, while simplified interesting methods to account for steady-state saturation, including cross-coupling effects, are still produced [7, 8].

The saturation curve family, $\Psi_d(I_q, I_d + I_{fd})$ and $\Psi_q(I_q, I_d + I_{fd})$ may be determined as follows from standstill flux decay tests.

8.6.7 Saturated Steady-State Parameters from Standstill Flux Decay Tests

To account for magnetic saturation, high (rated) levels of current in the stator and in the field winding are required. Under standstill conditions, the cooling system of the generator might not permit long time operation. The testing time should be reduced. Further on, with currents in both axes (I_q , $I_d + I_{fd}$), there will be torque, so the machine has to be stalled. Low-speed high-power SGs have large torque, and stalling is not easy.

If the tests are done in axis d or in axis q , there will be no torque, and the cross-coupling saturation (between orthogonal axes) is not present. Flux decay tests consist of first supplying the machine with a small DC voltage with stator phases connected so as to place the stator mmf either along axis d or along axis q . All this time, the field winding may be short-circuited, open, or supplied with a DC current. At a certain moment after the I_{ao} , V_o , and I_{Fo} are measured, the DC circuit is short-circuited by a fast switch

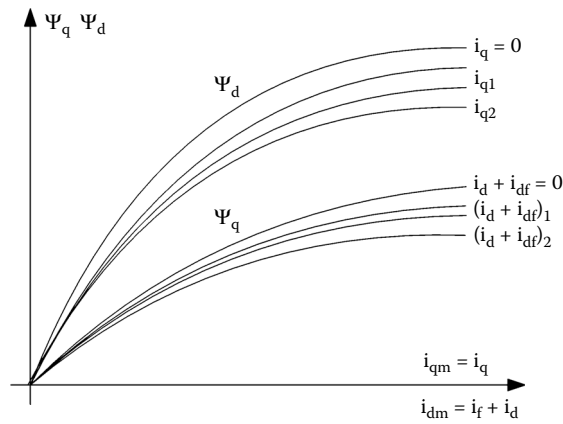


FIGURE 8.24 *d* and *q* axes flux vs. current curves family.

with a very low voltage across it (when closed). A free-wheeling diode may be used instead, but its voltage drop should be recorded and its integral during flux (current) decay time in the stator should be subtracted from the initial flux linkage. The *d* and *q* reactances are then obtained for the initial (DC) situation, corresponding to the initial flux linkage in the machine. The test is repeated with increasing values of initial currents along axes *d* ($i_d + i_{df}$) and *q* (i_q), and the flux current curve family as in Figure 8.24 is obtained. The same tests may be run on the field winding with an open- or short-circuited stator.

A typical stator connection of phases for *d* axis flux decay tests is shown in Figure 8.25a.

To arrange the SG rotor in axis *d*, the stator windings, connected as in Figure 8.25a, are supplied with a reasonably large DC current with the field winding short-circuited across the free-wheeling diode. If the rotor is heavy and it will not move by itself easily, the stator is fed from an AC source with a small

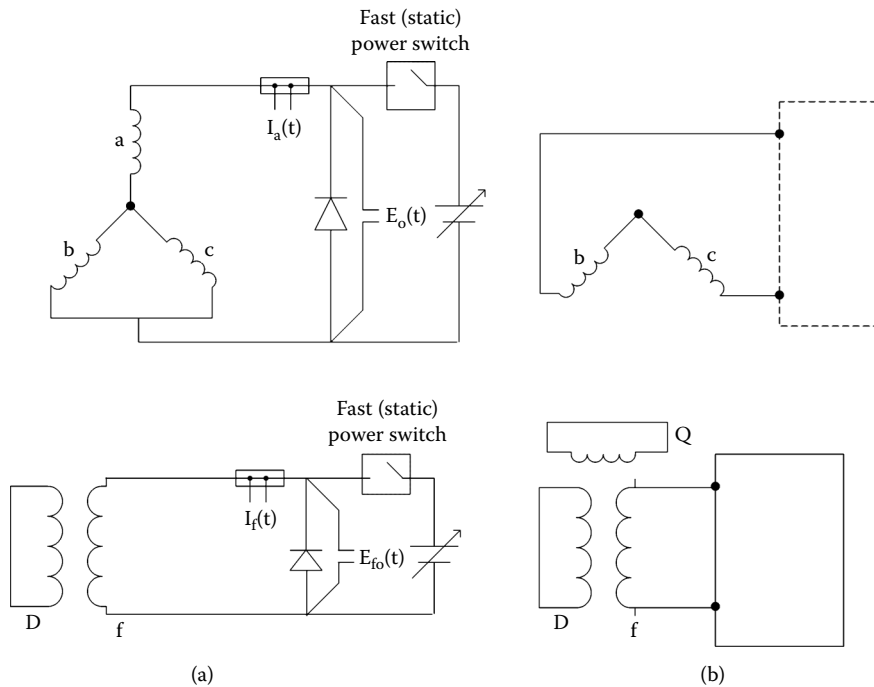


FIGURE 8.25 Flux decay tests: (a) axis *d* and (b) axis *q*.

current, and the rotor is rotated until the AC field-induced current with the free-wheeling diode short-circuited will be at maximum. Alternatively, if phases b and c in series are AC supplied (Figure 8.25b), then the rotor is moved until the AC field-induced current becomes zero. For fractionary stator winding, the position of axis d is not so clear, and measurements in a few closely adjacent positions are required in order to average the results [1].

The SG equations in axes d and q at zero speed are simply

$$I_d R_a - V_d = -\frac{d\Psi_d}{dt} \quad (8.82)$$

$$I_q R_a - V_q = -\frac{d\Psi_q}{dt} \quad (8.83)$$

In axis d (Figure 8.25a),

$$i_d = \frac{2}{3} \left(i_a + i_b \cos\left(\frac{2\pi}{3}\right) + i_c \cos\left(-\frac{2\pi}{3}\right) \right) = i_a \quad (8.84)$$

$$i_q = \frac{2}{3} \left(0 + i_b \sin\left(\frac{2\pi}{3}\right) + i_c \sin\left(-\frac{2\pi}{3}\right) \right) = 0 \quad ; \quad i_b = i_c \quad (8.85)$$

The flux in axis q is zero. After short-circuiting the stator ($V_d = 0$) and integrating (8.82),

$$R_a \int_0^\infty I_d dt + K_d \int_0^\infty V_{diode} dt = (\Psi_d)_{initial} - (\Psi_d)_{final} \quad (8.86)$$

$$K_d = 2/3 \text{ as } V_d = V_a \text{ and } V_a - V_b = (2/3)V_a \quad (8.87)$$

Equation 8.86 provides the key to determining the initial flux linkage if the final flux linkage is known. The final flux is produced by the excitation current alone and may be obtained from a flux decay test on the excitation, from same initial field current, with the stator open, but this time, recording the stator voltage across the diode $V_o(t) = V_{abc}(t)$ is necessary. As $V_{abc}(t) = (3/2)V_d(t)$,

$$\Psi_{dinitial}(i_{fo}) = \int_0^\infty \frac{2}{3} V_o(t) dt; \quad i_a = 0 \quad (8.88)$$

The initial d axis flux $\Psi_{dinitial}$ is as follows:

$$\Psi_{dinitial}(i_{fdo} + i_{do}) = L_l i_{do} + L_{ad}(i_{fdo} + i_{do}) \quad (8.89)$$

As i_f and not i_{fd} (reduced to the stator) is measured, the value for the ratio a has to be determined first. It is possible to run a few flux decay tests on the stator, with zero field current, and then in the rotor, with zero stator current, and use the above procedure to calculate the initial flux (final flux is zero). When the initial flux in the stator from both tests is the same (Figure 8.26), then the ratio of the corresponding currents constitutes the reduction (turn ratio) value a :

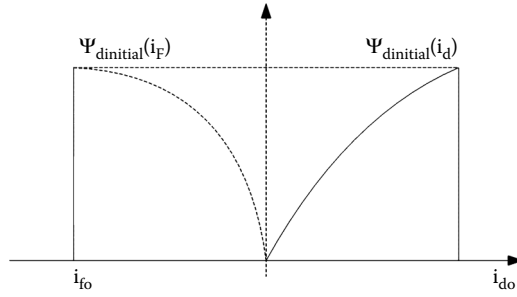


FIGURE 8.26 Turns ratio $a = i_{do}/i_{fo}$.

$$a = \frac{i_{do}}{i_{fo}} \quad i_{fd} = a i_f \quad (8.90)$$

The variation of a with the level of saturation should be small. When the tests are done in axis q (Figure 8.25b),

$$i_d = 0 \quad i_b = -i_c \quad i_a = 0 \quad (8.91)$$

$$i_q = \frac{2}{3} \left(i_b \sin \left(\frac{2\pi}{3} \right) + i_c \sin \left(-\frac{2\pi}{3} \right) \right) = \frac{2}{\sqrt{3}} i_b \quad (8.92)$$

$$V_q = \frac{2}{3} \left(V_a \sin \theta + (V_b - V_c) \sin \frac{2\pi}{3} \right) = \frac{2}{3} (V_b - V_c) \frac{\sqrt{3}}{2} = \frac{V_b - V_c}{\sqrt{3}} \quad (8.93)$$

Under flux decay, from Equation 8.53 with Equation 8.92 and Equation 8.93,

$$\Psi_{qinitial}(i_{qo}, i_{fdo}) = \frac{2}{\sqrt{3}} \int i_b R_a dt + \frac{1}{\sqrt{3}} \int_0^\infty V_{diode} dt \quad (8.94)$$

The final flux in axis q is zero, despite the nonzero field current, because the two axes are orthogonal.

Doing the tests for a few values of $i_{fdo}(i_{fo})$ and for specified initial values of $i_{qo} = \frac{2}{\sqrt{3}} i_b$, a family of curves may be obtained:

$$\Psi_{qinitial}(i_{qo}, i_{fdo}) = L_l I_{qo} + I_{qo} L_{aq}(i_{qo}, i_{fdo}) \quad (8.95)$$

Considering that the d axis stator current and field current mmfs are almost equivalent, the cross-coupling saturation in axis q is solved for all purposes. This is not so in axis d , where no cross-coupling has been explored. A way out of this situation is to “move” the stator mmf connected as in Figure 8.25 by exchanging phases from $a-b$ and c to $b-a$ and c to $c-a$ and b . This way, the rotor is left in the d axis position corresponding to $a-b$ and c (Figure 8.25). Now, I_d , I_q , V_d , and V_q have to be considered together; thus, both families of curves may be obtained simultaneously, with

$$i_d = \frac{2}{3} \left[i_a \cos(-\theta_{er}) + i_b \cos\left(-\theta_{er} + \frac{2\pi}{3}\right) + i_c \cos\left(-\theta_{er} - \frac{2\pi}{3}\right) \right] \quad (8.96)$$

$$i_q = \frac{2}{3} \left[i_a \sin(-\theta_{er}) + i_b \sin\left(-\theta_{er} + \frac{2\pi}{3}\right) + i_c \sin\left(-\theta_{er} - \frac{2\pi}{3}\right) \right] \quad (8.97)$$

V_d and V_q are obtained with similar formulae, but notice that $V_b = V_c = -V_a/2$. Then, the flux decay equations after integration are as follows:

$$\Psi_{dinitial} = \Psi_{dfinal} + \int_0^\infty i_d R_a dt + \frac{V_{d0}}{V_{abco}} \int_0^\infty V_{diode} dt \quad (8.98)$$

$$\Psi_{qinitial} = \Psi_{qfinal} + \int_0^\infty i_q R_a dt + \frac{V_{q0}}{V_{abco}} \int_0^\infty V_{diode} dt \quad (8.99)$$

The final values of flux in the two axes are produced solely by the field current. The flux decay test in the rotor is done again to obtain the following:

$$\Psi_{dinitial}(i_{fo}) = \int_0^\infty V_d(t) dt \quad (8.100)$$

$$\Psi_{qinitial}(i_{fo}) = \int_0^\infty V_q(t) dt \quad (8.101)$$

Placing the rotor in axis d , then in axis q , and then with $\theta_{er} = \frac{\pi}{6}$, $\frac{2\pi}{3}$ will produce plenty of data to document the flux/current families that characterize the SG (Figure 8.24). Flux decay test results in axis d or axis q in large SGs to determine steady-state parameters as influenced by saturation were published [9], but the procedure — standard in principle — has to be further documented by very neat tests with cross-coupling thoroughly considered, and with hysteresis and temperature influence on results eliminated.

The flux decay tests at nonzero or non-90° electric angle, introduced above, might be the way to obtain the whole flux/current (or flux/mmF) family of curves that characterizes the SG for various loads. Note that it may be argued that, though practically all values of i_d , i_q , and i_{fd} may be produced in flux decay tests, the saturation influence on steady-state parameters may differ under load for the same current triplet. This is true because under load (at rated speed), the stator iron is AC magnetized (at frequency f_N) and not DC magnetized as in flux decay tests.

Direct-load tests or FEM comparisons with these flux decay tests will tell if this is more than an academic issue. The whole process of standstill flux decay tests may be computerized and, thus, mechanized, as static power switches are now available off the shelf. The tests take time, but apparently notably less time than the SSFR test. The two types of tests are, in fact, complementary, as one produces the steady-state (or static) saturated parameters for specified load conditions, while the other estimates the parameters for transients from such initial on-load steady-state states. The standstill flux decay tests were also used to estimate the parameters for transients by curve fitting the current decays vs. time [10, 11].

8.7 Tests To Estimate the Subtransient and Transient Parameters

Subtransient and transient parameters of the SG manifest themselves when sudden changes at or near stator terminals (short-circuits) or at the field current occur. Knowing the sudden balanced and unbalanced short-circuit stator current peak value and evolution in time until steady state is useful in the design of SG protection, calibration of the trip stator and field-current circuit breakers, and calculation of the mechanical stress in the stator end turns. Sudden short-circuit tests from no-load or load operation have been performed for more than 80 years, and, in general, two stages during these transients were traditionally identified.

The first, short in duration, characterized by steep attenuation of stator current I_s , is called the subtransient stage. The second, larger and slower in terms of current decay rate is the so-called transient stage. Phenomenologically, in the transient stage, the transient currents in the rotor damper cage (or solid rotor) are already fully attenuated. Subtransient and transient stages are characterized by time constants: the time elapsed for a current decay to $1/e = 0.368$ from its original value. Based on this observation, graphical methods were developed to identify the subtransient and transient parameters. As short-circuits from no load are typical, only the d axis parameters are obtained in general (X_d'' , T_d'' , X_d' , T_d').

In acquiring the armature and field current during short-circuit, it is important to use a power switch that short-circuits all required phases in the same time. Also, noninductive shunts or Hall probe current sensors with leads kept close together or twisted or via optical fiber cables to reduce the induced parasitic voltages are to be used.

To avoid large errors and high transient voltage in the field circuit, the latter has to be supplied from low-impedance constant voltage supply. For the case of brushless exciters, the field current sensor is placed on the rotor, and its output is transmitted through special slip-rings and brushes placed on purpose there, or through telemetry.

8.7.1 Three-Phase Sudden Short-Circuit Tests

The standard variation of stator terminal RMS AC components of current during a three-phase sudden short-circuit from no load is as follows:

$$I_{ac}(t) = \frac{E}{X_{ds}} + \left(\frac{E}{X_d'} + \frac{E}{X_{ds}} \right) e^{-t/T_d'} + \left(\frac{E}{X_d''} + \frac{E}{X_{ds}} \right) e^{-t/T_d''} \quad (8.102)$$

where

$I(t)$ = the AC RMS short-circuit current (P.U.)

$E(t)$ = the no-load (initial) AC RMS phase voltage (P.U.)

If the test is performed below 0.4 P.U. initial voltage, X_{ds} is replaced by X_{du} (unsaturated), with both taken from the open-circuit saturation curve.

After subtracting the sinusoidal (steady-state) term in Equation 8.93, the second and third terms may be represented in semilogarithmic scales. The rapidly decaying portion of this curve represents the subtransient stage, while the straight line is the transient stage (Equation 8.102).

The extraction of rms values of the stator AC short-circuit current components from its recorded waveform vs. time is now straightforward. If the field current is also acquired, the stator armature time constant T_a may also be determined. The DC decay stator short-circuit current components from all three phases may also be extracted from the recorded (acquired) data.

If a constant-voltage low-impedance supply to the field winding is not feasible, it is possible to simultaneously short-circuit the stator and the field winding. In this case, both the stator current and the field current decay to zero. From the stator point of view, the constant component in Equation 8.102

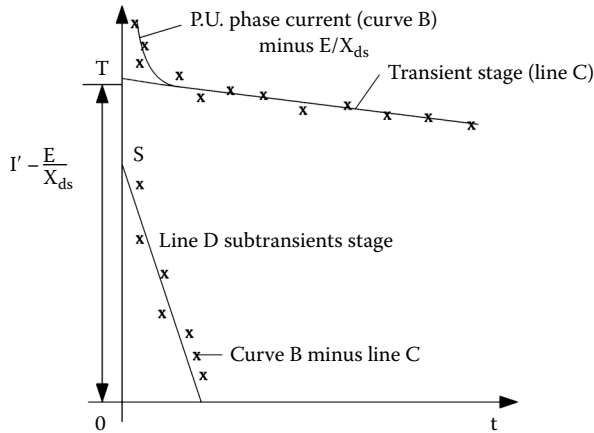


FIGURE 8.27 Analysis of subtransient and transient short-circuit current alternating current components.

has to be eliminated. It is also feasible to reopen the stator circuit (after reaching steady short-circuit) and record the stator voltage recovery.

The transient reactance X'_d is as follows:

$$X'_d = \frac{E}{I'} \quad (8.103)$$

I' is the initial AC transient current (OT Figure 8.27) plus the steady-state short-circuit current E/X_d .

The subtransient reactance X''_d is

$$X''_d = \frac{E}{I''} \quad (8.104)$$

I'' is the total AC peak at the time of short circuit $I'' = I' + \overline{OS}$ (from Figure 8.27).

The transient reactance is influenced by the saturation level in the machine. If X'_d is to be used to describe transients at rated current, short-circuit tests are to be done for various initial voltages E to plot $X'_d(I')$. The short-circuit time constants T'_d and T''_d are obtained as the slopes of the straight lines C and D in Figure 8.27.

8.7.2 Field Sudden Short-Circuit Tests with Open Stator Circuit

The sudden short-circuit stator tests can provide values for X''_d , X'_d , T''_d , and T'_d . The stator open-circuit subtransient and transient time constants T''_{d0} and T'_{d0} are, however, required to fully describe the operational impedance X_d . A convenient test to identify T'_{d0} consists of running the machine on armature open circuit with the field circuit provided with a circuit breaker and a field discharge contact with a field discharge resistance (or free-wheeling diode) in series. The field circuit is short-circuited by opening the field circuit breaker (Figure 8.28a).

The field current and stator voltage are acquired and represented in a semilogarithmic scale (Figure 8.28b).

The transient open-circuit time constant T'_{d0t} in Figure 8.28b accounts also for the presence of additional discharge resistance R_D . Consequently, the actual T'_{d0} is as follows:

$$T'_{d0} = T'_{d0t} \cdot \left(1 + \frac{R_D}{R_{fd}} \right) \quad (8.105)$$

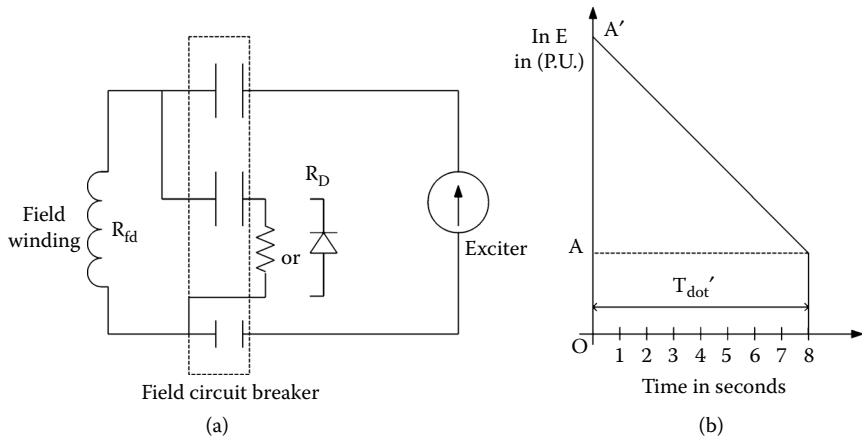


FIGURE 8.28 Field-circuit short-circuit tests with open armature: (a) the test arrangement and (b) the armature voltage E vs. time.

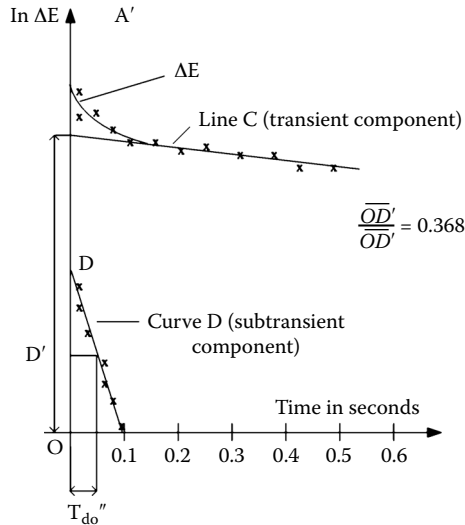


FIGURE 8.29 Difference between recovery voltage and steady-state voltage vs. time.

When a free-wheeling diode is used, R_D may be negligible.

The subtransient open-circuit time constant T_{do}'' may be obtained after a sudden short-circuit test when the stator armature circuit is suddenly opened and the recovery armature differential voltage is recorded (Figure 8.29). The value of T_{do}'' is obtained after subtracting the line C (Figure 8.29) from the differential voltage ΔE (recovery RMS voltage minus RMS steady-state voltage) to obtain curve D, approximated to a straight line. Notice that the three-phase short-circuit tests with variants provided only transient and subtransient parameters in axis d .

8.7.3 Short-Circuit Armature Time Constant T_a

The stator time constant T_a occurs in the DC component of the three-phase short-circuit current:

$$I_{dc}(t) = \frac{E}{X_d''} e^{-t/T_a} \quad (8.106)$$

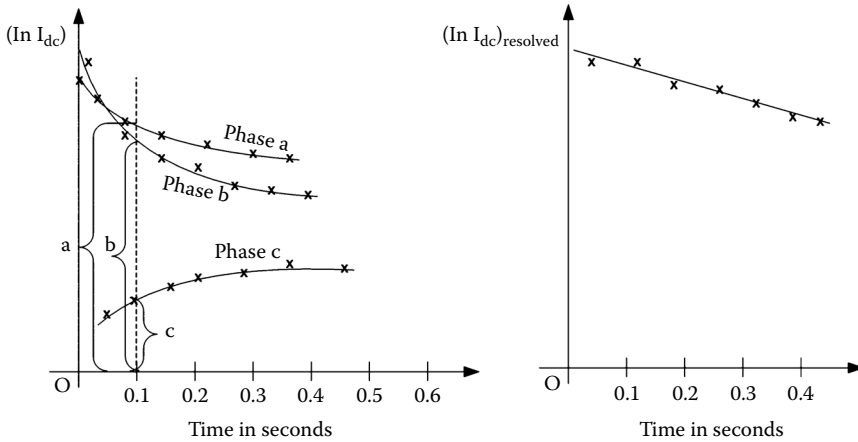


FIGURE 8.30 Direct current components of short-circuit currents.

It may be determined by separating the DC components from the short-circuit currents of phases a , b , and c (Figure 8.30).

As can be seen from Figure 8.30, the DC components of short-circuit currents do not vary in time in exactly the same way. A resolved I_{dc} is calculated, from selected values at the same time, as follows [1]:

$$(I_{dc})_{resolved} = \left(\sqrt{(a^2 + b^2 - ab)} + \sqrt{a^2 + c^2 - ac} + \sqrt{b^2 + c^2 - cb} \right) \sqrt{\frac{4}{27}} \quad (8.107)$$

where a , b , and c are the instantaneous values of I_a , I_b , and I_c for a given value of time with $a > b > c$. Then, from the semilogarithmic graph of $(I_{dc})_{resolved}$ vs. time, T_a is found as the slope of the straight line.

Note that the above graphical procedure to identify X_d'' , X_d' , T_d'' , T_d' , T_a , through balanced short-circuit tests may be computerized to speed up the time to extract these parameters from test data that are currently computer acquired [1].

Various regression methods were also introduced to fit the test data to the SG model.

8.7.4 Transient and Subtransient Parameters from d and q Axes Flux Decay Test at Standstill

The standstill flux decay tests in axes d and q provide the variation of $i_d(t)$ and $i_{fd}(t)$ and, respectively, $i_q(t)$ (Figure 8.31). This test was traditionally used to determine — by integration — the initial flux and, thus, the synchronous reactances and the turn ratio a . However, the flux decay transient current responses contain all the transient and subtransient parameters. Quite a few methods to process this information and produce X_d'' , X_d' , X_q'' , T_d'' , T_d' , T_q'' have been proposed. Among them, we mention here the decomposition of recorded current in exponential components [10]:

$$I_{d,q}(t) = \sum I_j e^{-t/T_j} \quad (8.108)$$

For the separation of the exponential constants I_j and T_j , a dedicated program based on nonlinear least square analysis may be used. Also, the maximum likelihood (ML) estimation was applied [11] successfully to process the flux decay data — $i_d(t)$, $i_{fd}(t)$ — with two rotor circuits in axes d and q . To initialize the process, the graphical techniques described in previous paragraphs [12] were also applied for the scope.

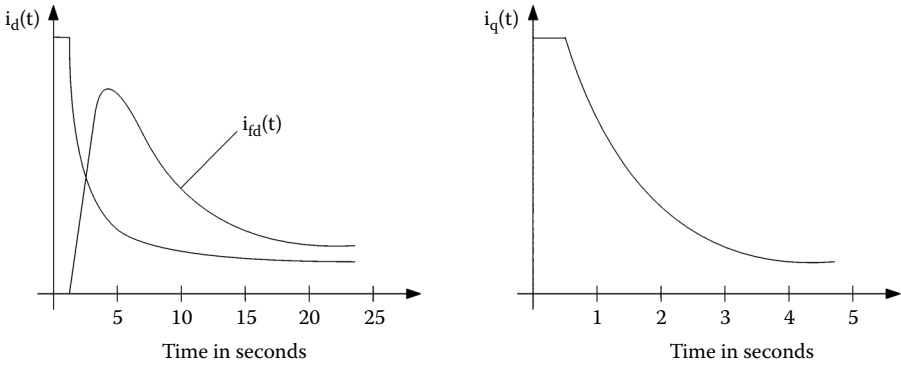


FIGURE 8.31 Flux decay transients at standstill.

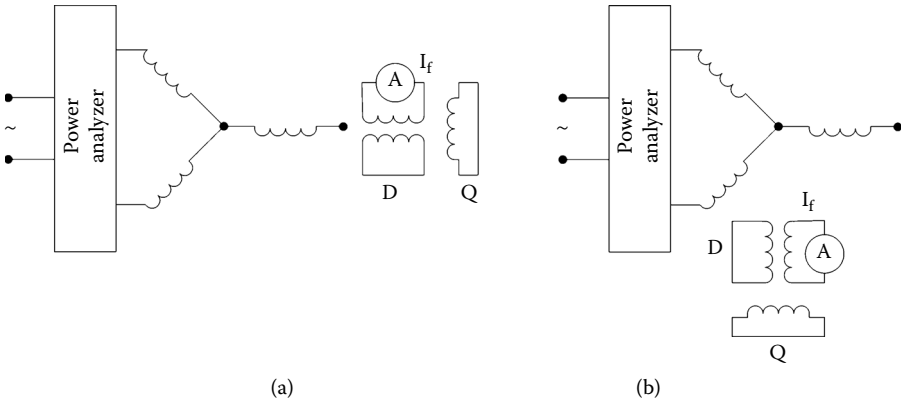


FIGURE 8.32 Line-to-line alternating current standstill tests: (a) axis d and (b) axis q .

If the tests are performed for low initial currents, there is no magnetic saturation. On the contrary, for large (rated) values of initial currents, saturation is present.

It may be argued that during the transients in the machine at speed and on load, the frequency content of various rotor currents differs from the case of standstill flux decay transients. In other words, were the transients and the subtransient parameters determined from flux decay tests applied safely? At least they may be safely used to evaluate balanced sudden short-circuit transients.

8.8 Subtransient Reactances from Standstill Single-Frequency AC Tests

The subtransient reactances X_d'' and X_q'' are associated with fast transients or large frequency (Figure 8.32a and Figure 8.32b). Consequently, at standstill when supplying the stator line from a single-phase AC (at rated frequency) source, the rotor circuits (field winding is short-circuited) experience that frequency. The rotor is placed in axis d by noticing the situation when the AC field current is maximum. For axis q , it is zero.

The voltage, current, and power in the stator are measured, and thus,

$$Z_{d,q}'' = \frac{E_{\parallel}}{2I_a} \quad (8.109)$$

$$R''_{d,q} = \frac{P_a}{2I_a^2} \quad (8.110)$$

$$X''_{d,q} = \sqrt{\left(Z''_{d,q}\right)^2 - \left(R''_{d,q}\right)^2} \quad (8.111)$$

The rated frequency f_N is producing notable skin effects in the solid parts of the rotor or in the damper cage. As for the negative impedance Z_2 , the frequency in the rotor $2f_N$, it might be useful to do this test again at $2f_N$ and determine again $X''_d(2f_N)$ and $X''_q(2f_N)$ and then use them to define the following:

$$X_2 = \frac{X''_d(2f_N) + X''_q(2f_N)}{2} \quad (8.112)$$

$$R_2 = \frac{R''_d(2f_N) + R''_q(2f_N)}{2} \quad (8.113)$$

It should be noticed, however, that the values of X_2 and R_2 are not influenced by DC saturation level in the rotor that is present during SG on load operation. If solid parts are present in the rotor, the skin effect that influences X_2 and R_2 is notably marked, in turn, by the DC saturation level in the machine at load.

8.9 Standstill Frequency Response Tests (SSFRs)

Traditionally, short-circuit tests have been performed to check the SG capability to withstand the corresponding mechanical stresses on one hand, and to provide for subtransient and transient parameter determination to predict transient performance and assist in SG control design, on the other hand. From these tests, two rotor circuit models are identified: the subtransient and transient submodels — a damper plus field winding along the d axis and two damper circuits along the q axis. As already illustrated in previous paragraphs, sudden short-circuit tests do not generally produce the transient and subtransient parameters in axis q .

For today's power system dynamics studies, all parameters along axes d and q are required.

Identification of the two rotor circuit models in axis d and separately in axis q may be performed by standstill flux decay tests as illustrated earlier in this chapter.

It seems, however, that both sudden short-circuit tests and standstill flux decay tests do not completely reflect the spectrum of frequencies encountered by an SG under load transients when connected to a power system or in stand-alone mode.

This is how standstill frequency tests have come into play. They are performed separately in axes d and q for current levels of 0.5% of rated current and for frequencies from 0.001 to 100 Hz and more.

Not all actual transients in an SG span this wide frequency band; thus, the identified model from SSFR tests may be centered on the desired frequency zone.

The frequency effects in solid iron-rotor SGs are very important, and thus, the second-order rotor circuit model may not suffice. A third order in both d and q axes proved to be better.

As with all standstill tests, the centrifugal effect on the contact resistance of damper bars (or on conducting wedges) to slot walls are not considered, although they may notably influence the identified model. Comparisons between SSFR and on-load frequency response tests for turbogenerators have spotted such differences. The saturation level is very low in SSFR tests, while in real SG transients, the rotor core is strongly DC magnetized, and the additional (transient) frequency currents in the solid iron occur in such an iron core. The field penetration depth is increased by saturation, and the identified model parameters change.

Running SSFR tests in the presence of increasing DC premagnetization through the field current may solve the problem of saturation influences on the identified model. DC premagnetization is required only for frequencies above 1 Hz. Thus, the time to apply large DC currents is somewhat limited, so as to limit the temperature rise during such DC plus SSFR tests. Recently, the researchers in Reference [12] seemed to demonstrate such a claim. So far, however, the pure SSFR tests were investigated in more detail through a very rich literature and were finally standardized [1].

In what follows, the standardized version of SSFR is presented with short notes on the latest publications about the subject [1, 13].

8.9.1 Background

The basic small perturbation transfer function parameters, as developed in Chapter 5, are as follows:

$$\Delta\Psi_d(s) = G(s)\Delta e_{fd}(s) - L_d(s)\Delta i_d(s) \quad (8.114)$$

$$\Delta\Psi_q(s) = -L_q(s)\Delta i_q(s) \quad (8.115)$$

where

$L_d(s)$ = the direct axis operational inductance (the Laplace transform of d axis flux divided by i_d with field-winding short-circuited $\Delta e_{fd} = 0$)

$L_q(s)$ = the quadrature axis operational inductance

$G(s)$ = the armature to field transfer function (Laplace transform of the ratio of d axis flux linkage variation to field voltage variation, when the armature is open circuited)

The “—” signs in Equation 8.114 and Equation 8.115 are common for generators in the United States.

Also,

$$sG(s) = \left(\frac{\Delta i_d(s)}{\Delta i_{fd}(s)} \right)_{\Delta e_{fd}=0} \quad (8.116)$$

Equation 8.116 defines the $G(s)$ for the case when the field winding is short-circuited.

One more transfer function is $Z_{af0}(s)$:

$$Z_{af0}(s) = \left(\frac{\Delta e_{fd}(s)}{\Delta i_d(s)} \right)_{\Delta i_{fd}=0} \quad (8.117)$$

This represents the Laplace transform of the field voltage to d axis current variations when the field winding is open. Originally, the second-order rotor circuit model (Figure 8.33; Chapter 5) was used to fit the SSFR.

The presence of the leakage coupling inductance L_{fld} introduced in Reference [14] to better represent the field-winding transients was found positive in cylindrical solid-iron rotors and negative in salient-pole SGs.

In general, the stator leakage inductance L_l is considered known.

For high-power cylindrical solid-rotor SGs, third-order models were introduced (Figure 8.34). There is still a strong debate over whether one or two leakage inductances are required to fully represent such a machine, where the skin effect in the solid iron (and in the possible copper damper strips placed below the rotor field-winding slot wedges) is notable. Eventually, they lead to rather complex frequency responses (Figure 8.34 and Figure 8.35) [15].

With the leakage inductance L_l given, it is argued whether both L_{f12d} and L_{f2d} are necessary to fully represent the actual phenomena in the machine. Though linear circuit theory allows for a few equivalent circuits for the same frequency response over some given frequency bands, it seems natural to follow the physical phenomena flux paths in the machine (Figure 8.35) [15].

Initially, SSFR methods made use of only stator inductances $L_d(\omega)$, $L_q(\omega)$ responses. It was soon realized that, simultaneously, the rotor response transfer function $G(\omega)$ has to be taken into consideration so that the modeling of the transients in the field winding would be adequate. In addition, $Z_{afd}(j\omega)$ is identified in some processes if the frequency range of interest is below 1 Hz.

The magnitudes and the phases of $L_d(j\omega)$, $L_q(j\omega)$, $G(j\omega)$, and $Z_{af0}(j\omega)$ are measured at several frequencies. The smaller the frequencies, the larger the number of measurements per decade (up to 60) required for satisfactory precision [16].

SSFR tests are done at very low current levels (0.5% of base stator current) in order to avoid overheating, as, at least in the low frequency range, data acquisition for two to three periods requires long time intervals ($f = 0.001$ to 1000 Hz).

Although magnetic saturation of the main flux path is avoided, the SSFR makes the stator and rotor-iron magnetization process evolve along low amplitude hysteresis cycles, where the incremental permeability acts $\mu_i = (100 \text{ to } 150)\mu_o$. Consequently, L_{ad} and L_{aq} identified from SSFR are not to be used as unsaturated values with the machine at load. The SSFR measurable parameters are as follows:

$$Z_d(j\omega) = \frac{\Delta e_d(j\omega)}{\Delta i_d(j\omega)} \bigg|_{\Delta e_{fd}=0} \quad (8.118)$$

$$Z_q(j\omega) = \frac{\Delta e_q(j\omega)}{\Delta i_q} \quad (8.119)$$

$$G(j\omega) = \frac{\Delta e_d(j\omega)}{j\omega \Delta i_{fd}(j\omega)} \bigg|_{\Delta i_d=0} \quad (8.120)$$

$$j\omega G(j\omega) = \frac{\Delta i_{fd}(j\omega)}{\Delta i_d(j\omega)} \bigg|_{\Delta e_{fd}=0} \quad (8.121)$$

$Z_d(j\omega)$ and $j\omega G(j\omega)$ may be found from the same test (in axis d) by additionally acquiring the field current $i_{fd}(j\omega)$.

The measurable parameter $Z_{af0}(j\omega)$ is as follows:

$$Z_{af0}(j\omega) = \frac{\Delta e_{fd}(j\omega)}{\Delta i_d(j\omega)} \bigg|_{\Delta i_f=0} \quad (8.122)$$

or

$$Z_{af0}(j\omega) = \frac{\Delta e_d(j\omega)}{\Delta i_{fd}(j\omega)} \bigg|_{\Delta i_d=0} \quad (8.123)$$

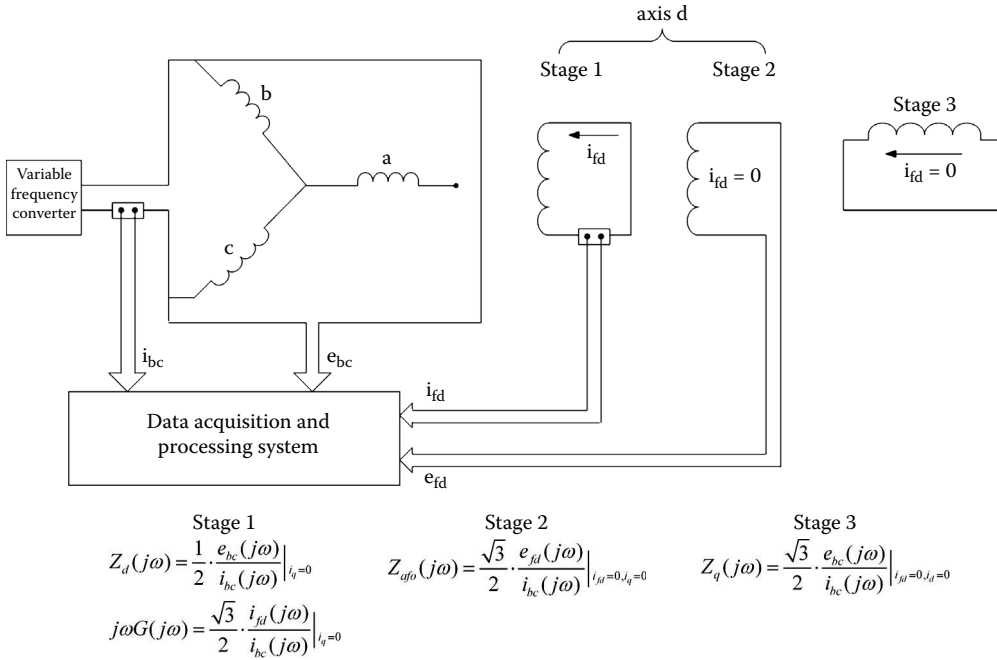


FIGURE 8.36 Standstill frequency response (SSFR) testing setup stages and computation procedures.

The mutual inductance L_{afd} between the stator and field windings is

$$L_{afd} = \frac{2}{3} \lim_{\omega \rightarrow 0} \frac{Z_{af0}(j\omega)}{j\omega} \quad (8.124)$$

Alternatively, from Equation 8.121,

$$L_{afd} = \lim_{\omega \rightarrow 0} \frac{\Delta i_{fd}(j\omega)}{j\omega \cdot \Delta i_d(j\omega)} \Big|_{\Delta e_{fd}=0} \quad (8.125)$$

Here, R_{fd} is the field resistance plus the shunt and connecting leads.

The typical testing arrangement and sequence are shown in Figure 8.36.

The stator resistance R_a is

$$R_a = \lim_{\omega \rightarrow 0} |Z_d(j\omega)| \quad (8.126)$$

Though rather straightforward, Equation 8.126 is prone to large errors unless a resolution of 1/1000 is not available at very low frequencies [1]. Fitting a straight line in the very low frequency range is recommended.

If R_a from Equation 8.126 differs markedly compared to the manufacturer's data, it is better to use the latter value, because the estimation of time constants in $L_d(j\omega)$ would otherwise be compromised:

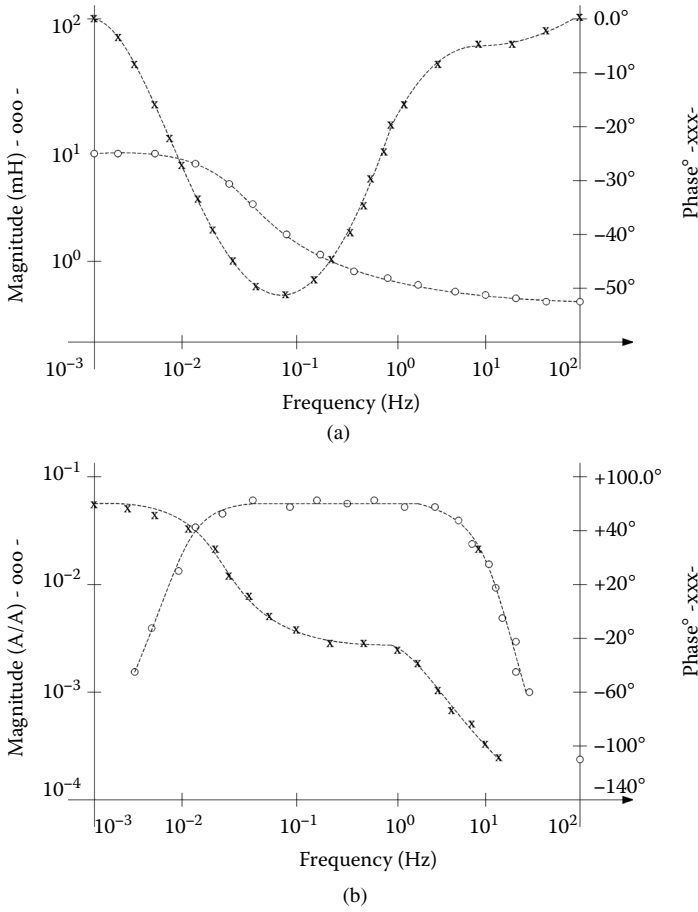


FIGURE 8.37 (a) $L_d(j\omega)$ and (b) $j\omega G(j\omega)$ typical responses.

$$L_d(j\omega) = \frac{Z_d(j\omega) - R_a}{j\omega} \quad (8.127)$$

Typical $L_d(j\omega)$ data are shown in Figure 8.37a, and data for $j\omega G(j\omega)$ are shown in Figure 8.37b.

The $Z_{af0}(j\omega)$ function is computed as depicted in Figure 8.36. The factor $\sqrt{3}/2$ in both $j\omega G(j\omega)$ and $Z_{af0}(j\omega)$ expressions (Figure 8.36) is due to the fact that stator mmf is produced with only two phases, or because phase b is displaced 30° with respect to field axis.

From quadrature tests, again, R_a is calculated as in axis d , and finally,

$$L_q(j\omega) = \frac{Z_q(j\omega) - R_a}{j\omega} \quad (8.128)$$

A typical $L_q(j\omega)$ dependence on frequency is shown in Figure 8.38. Moreover, the test results provide the value of the actual turns ratio $N_{af}(0)$:

$$N_{af0}(0) = \frac{1}{L_{ad}(0)} \lim_{\omega \rightarrow 0} \left| \frac{Z_{af0}(j\omega)}{j\omega} \right|_{i_q=0, i_d=0} \quad (8.129)$$

where $L_{ad}(0)$ is

$$L_{ad}(0) = \lim_{\omega \rightarrow 0} |L_d(j\omega)| \quad (8.130)$$

The base N_{af} turns ratio is as follows:

$$N_{af(base)} = \frac{3}{2} \left(\frac{I_{abase}}{I_{fdbase}} \right) = \frac{2p_1 N_f}{N_a} k_{w1} k_{f1} \quad (8.131)$$

where

- p_1 = the pole pairs
- N_f = the turns per field-winding coil
- K_{w1} = the total stator-winding factor
- K_{f1} = the total field form factor
- N_a = turns per stator phase

$N_{af}(0)$ and $N_{af}(base)$ should be very close to each other. The field resistance after reduction to armature winding R_{fd} is as follows:

$$R_{fd} = \frac{\lim_{\omega \rightarrow 0} (j\omega L_{ad})}{\lim_{\omega \rightarrow 0} \left(\frac{\Delta i_{fd}(j\omega)}{\Delta i_a(j\omega)} \right)} \cdot \frac{2}{3} N_{af}(0) \quad ; \quad (\Omega) \quad (8.132)$$

The directly measured field resistance r_{fd} may be reduced to armature winding to yield R_{fd} :

$$R_{fd} = r_{fd} \cdot \frac{3}{2} \cdot \frac{1}{N_{af}^2(0)} \quad ; \quad (\Omega) \quad (8.133)$$

Corrections for temperature may be added in Equation 8.133 if necessary.

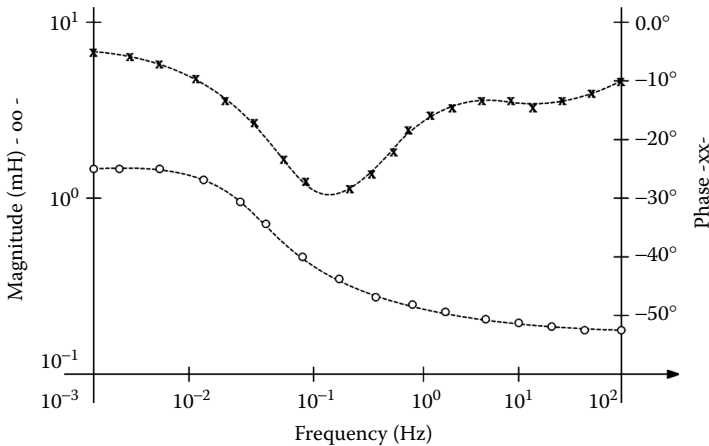


FIGURE 8.38 Typical $L_q(j\omega)$ response.

The base field current may be calculated from Equation 8.131 if the $N_{af}(0)$ value is used:

$$i_{fd}(base) = \frac{3}{2} I_a(base) \cdot \frac{1}{N_{af}(0)} \quad ; \quad A \quad (dc) \quad (8.134)$$

8.9.2 From SSFR Measurements to Time Constants

In a third-order model, $L_d(j\omega)$ or $L_q(j\omega)$ are of the following form:

$$L_{d,q}(j\omega) = L_{d,q}(0) \cdot \frac{(1 + j\omega T_{d,q}''')(1 + j\omega T_{d,q}'')(1 + j\omega T_{d,q}')}{(1 + j\omega T_{d,qo}''')(1 + j\omega T_{d,qo}'')(1 + j\omega T_{d,qo}')} \quad (8.135)$$

The time constants to be determined through curve fitting, from SSFR tests, are not necessarily the same as those obtained from short-circuit tests (in axis d). Numerous methods of curve fitting were proposed [16, 18], some requiring the computation of gradients and some avoiding them, such as the pattern search described in Reference [1].

The direct maximum likelihood method combining field short-circuit open SSFR in axis d was shown to produce not only the time constants, but also the parameters of the multiple-order models.

Rather straightforward analytical expressions to calculate the third-order model parameters from the estimated time constants were found for the case in which $L_{fd} = 0$ (see Figure 8.33) [19]. To shed more light on the phenomenology within the multiple-rotor circuit models, an intuitive method to identify the time constants from SSFR tests, based on phase-response extremes findings [20] is described in what follows.

8.9.3 The SSFR Phase Method

It is widely accepted that second-order circuit models have a bandwidth of up to 5 Hz and can be easily identified from SSFR tests. But even in this case, some simplifications are required to enable us to identify the standard set of short-circuit and open-circuit constants.

With third-order models, such simplifications are not indispensable. While curve-fitting techniques to match SSFR to the identified model are predominant today, they are not free from shortcomings, including the following:

- Define from the start the order for the model
- Initiate the curve fitting with initial estimates of time constants
- Define a cost function and eventually calculate its gradients

Alternatively, it may be possible to identify the time constants pairs $T_1 < T_{10}$, $T_2 < T_{20}$, and $T_3 < T_{30}$ (Equation 8.136) from the operational inductances $L_d(j\omega)$, $L_q(j\omega)$, and $j\omega G(j\omega)$, based on the property of lag circuits [20]:

$$L_d(j\omega) = L_d \frac{(1 + j\omega T_1)}{(1 + j\omega T_{10})} \cdot \frac{(1 + j\omega T_2)}{(1 + j\omega T_{20})} \cdot \frac{(1 + j\omega T_3)}{(1 + j\omega T_{30})} \quad (8.136)$$

The R–L branches in parallel that appear in the equivalent circuit of SGs, make pairs of zeros and poles when represented in the frequency domain. As each pair of zeros and poles forms a lag circuit ($T_1 < T_{10}$, $T_2 < T_{20}$, $T_3 < T_{30}$), they may be separated one by one from the phase response. Denote $T_1/T_{10} = \alpha < 1$.

The lag circuit main features are as follows:

- It has a maximum phase lag ϕ at the center frequency of the pole zero pair F_c , where

$$\sin \phi = \frac{\alpha - 1}{\alpha + 1} \quad (8.137)$$

- The overall gain change due to the zero/pole pair is as follows:

$$\text{gain change} = -20 \log \alpha \quad ; \quad (dB) \quad (8.138)$$

- The two time constants T_{pole} and T_{zero} are as follows:

$$T_{zero} = \frac{T_{pole}}{\alpha} \quad ; \quad T_{pole} = \frac{\sqrt{\alpha}}{2\pi F_c} \quad (8.139)$$

The gain change is, in general, insufficient to be usable in the calculation of α , but Equation 8.137 and Equation 8.139 are sufficient to calculate the zero and pole time constants. Identifying the maximum phase lag points ϕ (at frequency F_c) is first operated by Equation 8.137. Then, T_{pole} and T_{zero} are easily determined from Equation 8.139. The number of maximum phase-lag points in the SSFR frequency corresponds to the order of the equivalent circuit. The process starts by finding the first T_1 and T_{10} pair. Then, the pair is introduced in the experimentally found $L_d(j\omega)$ or $L_q(j\omega)$, and thus eliminated. The order of the circuit is reduced by one unit.

The remainder of the phase will be used to find the second zero-pole pair, and so on, until the phase response left does not contain any maximum.

The order of the equivalent circuit is not given initially but claimed at the end, in accordance with the actual SSFR-phase number of maximum phase-lag points.

The whole process may be computer programmed easily and ± 1 dB gain errors are claimed to be characteristic of this method [20]. To further reduce the errors in determining the value of the maximum phase-lag angle ϕ and the frequency at which it occurs, F_c sensitivity studies were performed. They showed that an error in F_c produces a significant error in the time constants T_{pole} and T_{zero} . α changes the time constants such that ψ varies notably at the same F_c [20].

So, if F_c is varied above and below the firstly identified value F_{c1} , the $L_d(j\omega)$ error varies from positive to negative values. When this error changes sign, the correct value of F_c has been reached (Figure 8.39a). For this “correct” value of F_c , the initially calculated value of α is changed up and down until the error changes sign.

The change in sign of phase error (Figure 8.39b) corresponds to the correct value of α . With these correct values, the final values of two time constants are obtained. A reduction in errors to $\pm 0.5^\circ$ and, respectively, to ± 0.1 dB are claimed by these refinements.

The equivalent rotor circuit resistances may be calculated from the time constants just determined through an analytical solution using a linear transformation [19]. As expected, in such an analytical process, the stator leakage inductance L_l plays an important role. There is a value of L_l above which the rotor circuit leakage inductances become negative. Design values of L_l were shown to produce good results, however.

A few remarks seem to be in order:

- The SSFR phase-lag maxima are used to detect the center frequencies of the zero-pole pairs in the multiple-circuit model of SG.
- The zero-pole pairs are calculated sequentially and then eliminated one by one from the phase response until no maximum phase-lag is apparent. The order of the circuit model appears at the end of the process.

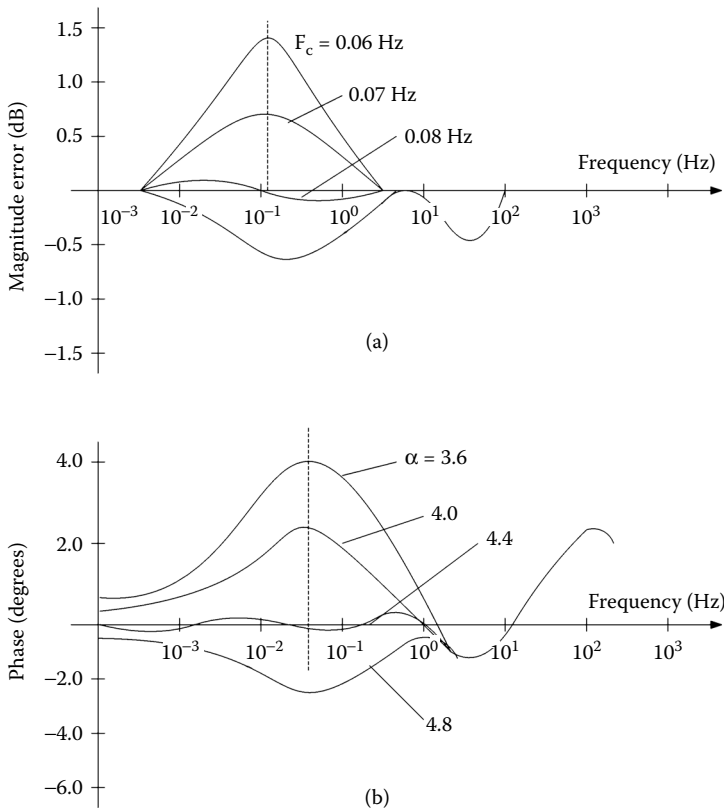


FIGURE 8.39 Variation of errors (a) in amplitude and (b) in phase.

- As the initial values of the time constants are determined from the phase response maxima, the process of optimizing their values as developed above leads to a unique representation of the equivalent circuit.
- It may be argued that the leakage coupling rotor inductances L_{j1d} , L_{j2d} are not identified in the process.
- The phase method may be at least used as a very good starting point for the curve-fitting methods to yield more physically representative equivalent circuit parameters of SGs.

8.10 Online Identification of SG Parameters

As today SGs tend to be stressed to the limit, even predictions of +5% additional stability margin will be valuable, as it allows for the delivery of about 5% more power safely. To make such predictions in a tightly designed SG and power system requires the identification of generator parameters from nondangerous online tests, such that a sudden variation of field voltage from one or a few active and reactive power levels [21].

This way, the dynamic parameter identification takes place in conditions closer to those encountered in even larger transients. During a specific on-load large transient, the parameters of the SG equivalent circuit may be considered constant, as identified through an estimation method [22], or variable with the level of magnetic saturation and temperature. Intuitively, it seems more acceptable to assume that magnetic saturation influences some (or all) of the inductances in the model, while the temperature influences the time constants. The frequency effects are considered traditionally by increasing the order of the rotor circuit model (especially for solid rotors). However, in a fast transient, the skin effect in the

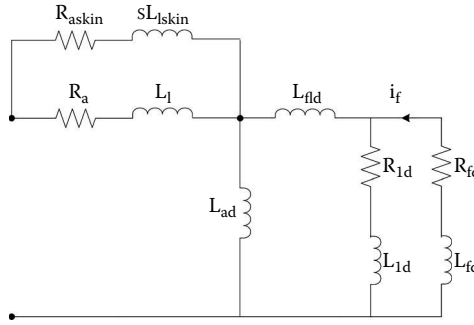


FIGURE 8.40 The addition of a fictitious circuit section to account for stator skin effect during fast transients.

stator winding of a large SG may be considerable. Also, during the first milliseconds of such a transient, the laminated core of stator may enter the model with an additional circuit [23].

When estimating the SG equivalent circuit parameters from rather large online measurements, it may be possible to let the parameters (some of them) vary in time, though in reality, they vary due to the magnetic saturation level that changes in time during transients.

The stator frequency effects may be considered either by adding one cage circuit to a model or by letting the stator resistance R_a vary in time during the process [24]. In the postprocessing stage, the variable parameters may be expressed as a function of, say, field current, power angle, or stator current. Such functions may be used in other online transients. Alternatively, for stator skin effect considerations, an additional fictitious circuit may be connected in parallel with R_a and L_l (Figure 8.40), instead of considering that R_a varies in time during transients. It may also be feasible to adopt a lower-order circuit model (say second order), perform a few representative online tests, and, from all the experimental data, determine the parameters. By making use of the values of these parameters through interpolation (artificial neural networks), for example, new transients may be explored safely [25]. Advanced estimation algorithms, such as using the concept of synthesized information factor (SIF) [24], artificial neural networks [25], constraint conjugate gradient methods [22], and maximum likelihood [26] have all been used for more or less successful validation on large machines under load, via transient responses in power angle, field current, and stator current [24]. The jury is still out, but, perhaps soon, an online measurement field strategy, with a pertinent parameter adaptive estimation scheme, will mature enough to enter the standards.

8.11 Summary

- An almost complete set of testing methods for synchronous generators (SGs) is presented in IEEE standard 115-1995. The International Electrotechnical Commission (IEC) has a similar standard.
- The SG testing methods may be classified into standardized and research types. The standardized tests may be performed for acceptance, performance, or parameters.
- Acceptance testing refers to insulation resistance dielectric and partial discharge, resistance measurements, identifying short-circuited field turns, polarity of field poles, shaft currents and bearing insulation, phase-sequence telephone-influence factor (balanced, residual, line to neutral) stator terminal voltage waveform deviation and distortion factors, overspeed tests, line discharging (maximum absorbed kilovoltampere at zero-power factor with zero field current), acoustic noise. They were presented in similar detail in this chapter following, in general, IEEE standard 115-1996.
- Testing an SG for performance refers to saturation curves, segregated losses, power angle, and efficiency.
- The individual loss components are as follows:
 - Friction and windage loss
 - Core loss (on open circuit)

- Strayload loss (on short-circuit)
- Stator winding loss
- Field winding loss
- To identify the magnetic saturation curves and then segregate the loss components and to finally calculate efficiency under load, four methods have gained wide acceptance:
 - Separate driving method
 - Electric input method
 - Retardation method
 - Heat transfer method
- The separate driving method is based on the concept of driving the SG at precisely controlled (or rated) speed by an external, low rating (<5% of SG rating) motor, or by the exciter (if it contains an electric machine on shaft) or by the prime mover. With the SG driven at rated speed, on open stator circuit, the field current, stator voltage, and the driving motor output are measured for increasing values of field current, until the stator terminal voltage reaches at least 125% of rated value. The open-circuit saturation curve is thus obtained. In addition, as the driving motor output is considered to be known, the field current may be made zero, and thus, the friction and windage losses are measured. From the open-circuit run, where friction and windage and core losses occur, the core loss for various values of terminal voltage is obtained. The same arrangement may be used to determine the short-circuit saturation curve and then the strayload losses for currents levels from 125 to 25% of rated current, if the winding resistance is known from previous measurements. With all loss components known, the efficiency vs. power output may be calculated.
- The electrical input method is similar to the separate driving method, but this time, the SG works as a synchronous motor without a mechanical load.
- In retardation tests, the uncoupled SG is brought at 105 to 110% of rated speed and then left to decelerate in three different situations:
 - Open-circuit stator, zero-field current, to measure friction and windage loss P_{fw} a.
 - Open-circuit stator, constant field current, to measure friction and windage loss + core loss: $P_{fw} + P_{core}$ b.
 - Short-circuit stator, constant field current, to measure friction and windage + stator winding + strayload losses: $P_{cu1} + P_{strayload} + P_{fw}$ c.

The inertia may be obtained from run (a), with P_{fw} already known, from the motion equation, by calculating the speed slowing rate around rated speed. Speed has to be recorded. Then, from runs (b) and (c), P_{core} and $P_{strayload}$ may be segregated.

- The other purpose of steady-state tests is to determine the steady-state parameters of SG and the field current under specified load.
- The leakage reactance X_l is approximated usually to the Potier reactance X_p obtained from a rated current zero-power-factor tests at rated voltage. As $X_p > X_l$ at rated voltage, the same test is performed at 110% rated voltage when X_p approaches X_l .
- A procedure to estimate X_l as the average between the zero sequence (homopolar) reactance X_o ($X_o < X_l$) and the reactance without the rotor inside the stator bore X_{lair} , is introduced. Alternatively, from X_{lair} , the bore air volume reactance X_{air} may be subtracted to obtain the leakage reactance. X_{air} is proportional to the unsaturated uniform airgap reactance X_{adu} ; $X_{air} \sim X_{adu} * gK_f \pi / \tau$; $X_l = X_{lair} - X_{air}$.
- The excitation current at specified load — active and reactive power and voltage — is determined by the Potier diagram method. Magnetic saturation is considered the same in both axes. The power angle is needed for the scope and is computed by using the unsaturated values of quadrature axis reactance, as in Equation 8.29.
- From the simplified transient SG phasor diagram (Figure 8.14), the excitation current for stability studies is obtained.
- Voltage regulation — the difference between no-load voltage and terminal voltage for specified load and same field current — is calculated based on the computed field current at specified load.

- The power angle may be measured by encoders or other mechanical sensors. The power angle is the electrical angle between the terminal voltage and the field-produced emf.
- Temperature tests are required to verify the SG capability to deliver the rated or more power under conditions agreed upon by vendor and buyer. Four methods are described:
 - Conventional (direct) loading
 - Synchronous feedback (back-to-back) loading
 - Zero-power-factor tests
 - Open-circuit running plus short-circuit “loading”
- While direct loading may be done by the manufacturer only for small- and medium-power SGs, the same test may be performed after commissioning, with the machine at the power grid for all power levels.
- Back-to-back loading implies the presence of two coupled identical SGs with their rotors displaced mechanically by $2\delta_N/p_1$. The stator circuits of the two machines are connected together. One machine acts as a motor, the other acts as a generator. If an external low rating motor is driving the MS + SG set, then the former covers the losses in the two machines $2\Sigma P$. Care must be exercised to make the losses fully equivalent with those occurring with the SG under specified load.
- The zero-power-factor load test implies that the SG works as a synchronous condenser (motoring at zero mechanical load). Again, loss equivalence with actual conditions has to be observed.
- The open-circuit stator test for the field current at specified load is run, and the temperature rise until thermal steady state, Δt_{oc} , is measured. Further on, the short-circuit test at rated current is run until new thermal steady state is obtained for a temperature rise of Δt_{sc} . The SG total temperature is $\Delta t_{oc} + \Delta t_{sc}$ minus the temperature differential due to mechanical loss, which is duplicated during the tests.
- All the above tests imply efforts and have shortcomings, but the temperature rise for specified load is so important for SG life that it has to be measured, even if sophisticated FEM thermal-electromagnetic models of SGs are now available.
- Besides steady-state performance, behavior under transient conditions is also important to predict. To this end, the SG parameters for transients have to be identified. Power system stability studies rely on SG parameter knowledge.
- Per unit (P.U.) values are used in parameter definitions to facilitate more generality in results referring to SGs of various power levels. Only three base independent quantities are generally required: voltage, current, and frequency.
- For the rotor, Rankin defined a new base field current $i_{fbase} = I_{fbase} * X_{adu}$. I_{fbase} is the field current (reduced to the stator) that produces the rated voltage on the straight line of the no-load saturation curve. X_{adu} is the unsaturated d axis coupling reactance (in P.U.) between stator and rotor windings. Rankin's reciprocal system produces equal stator-to-field and field-to-stator P.U. reactances.
- The steady-state parameters X_d , X_q may be determined by a few carefully designed tests without loading the SG. Quadrature axis reactance X_q is more difficult to segregate, but pure I_q loading of the machine method provides for the X_q values.
- SGs may work with unbalanced load either when connected to the power system or in stand-alone mode. For steady state, by the method of symmetrical components, the value of $Z_2(X_2)$ may be found from a steady-state line-to-line short-circuit. The elimination of the third harmonics from the measured voltage is crucial in obtaining acceptable precision with this testing method.
- The zero-sequence (homopolar) reactance X_o is measured from a standstill AC test with all stator phases in series or in parallel. In general, $X_o \leq X_i$. A two line to neutral short-circuit test will also provide for X_o .
- The short-circuit ratio (SCR) = $1/X_d = I_{FNL}/I_{FSI}$. I_{FSI} is the field current from the three-phase short-circuit (at rated stator current). I_{FNL} is the field current at rated voltage and open circuit test. SCR today has typical values of 0.4 to 0.6 for high-power SGs.
- Due to magnetic saturation and its cross-coupling effect, all the methods to determine the steady-state parameters so far need special corrections to fit the results from direct on-load measurements.

Families of flux/current curves for axes d and q are required to be obtained from special operation mode tests, in order to have enough data to cope with on-load various situations.

- Standstill flux decay tests may provide the required flux/current families of curves. They imply short-circuiting the stator or field circuits and recording the currents. The tests are done in axis d or q or in a given rotor position.
- Integrating the resistive voltage drop in time, the initial (DC) flux linkage is obtained. Care must be exercised to avoid hysteresis-caused errors and to measure the resistance before each new test in order to eliminate temperature rise errors.
- To estimate the transient parameters — $X''_d, X'_d, T''_d, T'_d, X''_q, T''_q, X'_q, T'_q, T''_{d0}, T'_{d0}, T''_{q0}, T'_{q0}$ — two main types of tests were standardized:
 - Sudden three-phase short-circuit tests
 - Standstill frequency response (SSFR)
- Three-phase sudden short-circuit is used to identify the above parameters of a second-order model of SG in axis d and axis q . The methods to extract the parameters, from stator phase currents and field current recording, are essentially either graphical with mechanization by computer programs [27] or of regression type.
- Third-order models are required, especially in SGs with solid rotors, due to skin effect strong dependence on frequency in solid bodies.
- Alternatively, there are proposals to determine the parameters for transients from the already mentioned standstill DC flux decay tests, by processing the time variation of currents or voltages during these tests. Though good results were reported, the method has not yet met worldwide acceptance due to insufficient documentation.
- Standstill frequency response tests use similar arrangements as those of the DC flux decay tests. The SG is fed with about 0.5% rated currents at frequencies from 0.001 to 100 Hz and more. The input voltage, stator current, field-current rms values, and phase-lags are measured. The tests take time, as at least two to three periods have to be recorded at all frequencies.
- In general, the amplitude of the operational parameters $L_d(j\omega), L_q(j\omega), G(j\omega)$, and $Z_{af0}(j\omega)$ is used to extract the parameters of the third-order model along axes d and q : $X''_{d,q}, X'_{d,q}, I''_{d,q}, T''_{d,q}, I'_{d,q}, T'_{d,q}, T''_{d,q0}, T'_{d,q0}, T''_{q,q0}, T'_{q,q0}$, the stator resistance R_a , field-winding resistance R_{fb} , and the turns ratio between rotor and stator a . Numerous curve-fitting methods were introduced and improved steadily up to the present time.
- The presence of one or two leakage mutual rotor reactances in the third-order model, with the leakage stator reactance X_l given *a priori*, is still a matter of debate.
- These reactances seem mandatory (at least one of them) to represent correctly, in the same time, the transient behavior of SGs seen from the stator circuit and from the field current side.
- The up to now less favored information from SSFR, the phase response vs. frequency, was recently put to work to identify the third model of SG [20]. The method is based on the observation that the phase response corresponds to zero/pole pairs in the model's transfer function. By using the center frequency F_C and the value of response phase, these maximum phase zero/pole pairs — time constants — are calculated rather simply. They are then corrected until only very low errors persist. After the first pair is identified, its circuits are eliminated from the response. The search for the phase maximum continues until no maximum persists. The model order comes at the end. Determining the resistances and reactances of the SG multiple circuit model, from transient reactances to time constants, may be done by regression methods. Analytical expressions were also found for the third-order models [19].
- Some verifications of the validity of SSFR test results for various large on-load transients were made. Still, this operation seems to be insufficiently documented, especially for solid-rotor SGs.
- On-line SG model identification methods, based on same nondamaging transients on-load (such as up to 30% step field voltage change response at various load conditions), were introduced recently. Artificial neural networks and other learning methods may be used to extend the model thus obtained to new transients, based on a set of representative on-load tests.

- While these complex online adaptive parameter identification methods go on, there are still hopes that simpler methods, such as standstill flux decay tests, standstill DC + SSFR tests, or load recovery tests, may be improved to the point that they become fully reliable for large on-load transients.
- Important developments are expected in SG testing in the near future, as theory, software, and hardware are continuously upgraded through worldwide efforts by industry and academia. These efforts are driven by ever-more demanding power quality standards.

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